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Battery electric vehicles: Progress, power electronic converters, strength (S), weakness (W), opportunity (O), and threats (T)

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ABSTRACT

The rely on internal combustion engines is gradually decreased with the recent evolution of electric vehicles (EVs) in the automotive industry. Electric motors are replacing the energy systems mainly to improve the powertrain's efficiency and ensure they are environmentally friendly. These novel powertrains are designed to operate solely on batteries or supercapacitors. For these types of EVs, the battery is charged using an alternating current supply in connection to the grid in the case of plug-in electric vehicles. Internal combustion engines are equally used for some hybrid vehicles. Charging of the battery can also be carried out via regenerative braking from the traction motor. This study presents a brief background about the different available EVs, detailed information on various power converter electronics used in battery electric vehicles, and a summary of the strengths (S), weaknesses (W), opportunities (O), and threats (T) of the EV is presented. Moreover, SWOT analysis of the battery electric vehicles (BEV) and their prospects in the automotive industry are introduced.

1. Introduction

The environmental drawbacks of using fossil fuels and the concerning world dependency on them despite their limited amount have drawn a lot of attention to the search for greener and more environmentally friendly alternatives [1–3]. Although waste heat recovery [4–8] could improve the efficiency of intensive energy consumption industries such as cement [9,10], aluminium [11,12], ceramic [13,14], etc., it will not significantly control global warming as such processes operate using fossil commodities. Renewable energy resources such as solar thermal [15–18], solar PV [19,20], geothermal [21,22], biomass [23–26], etc., are considered the most affordable way to control global warming and replace fossil fuels in various applications. However, most renewable energy sources are intermittent, so it needs a proper storage system [27–29]. The transportation sector is one of the most significant contributors to greenhouse gas emissions (GHG) [30]. The Automotive industry is under watch today as it is one of the biggest contributor to the global carbon emission emitted into the atmosphere [31]. Therefore, researchers have been compelled to consider a paradigm shift, especially with unstable prices of fossil commodities coupled with environmental issues, as explained earlier [32–34]. Moreover, the efficiency of the internal combustion engine is nearly 20% as the rest of the energy goes back as heat and pollutants released directly into the atmosphere. Today, electric vehicles (EVs) are the revolutionary option to transport in the automotive sector, with many research activities being conducted [35,36]. They are easy to operate, have fewer movable parts, and produce less heat. These systems tend to have higher efficiency (85 – 90% efficient) than the other option, and they are environmentally friendly, have higher torque, and have quick starting and stopping [37]. With the advancement in most renewable energy systems, the EV market will equally experience an appreciable market over time [38,39]. In sustainable city design, EVs are used for transportation due its advantages mentioned before [40–42]. Several alternative fueled vehicles are proposed, such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). Electric vehicles have earned a lot of attention over the past few years and continue to grow in popularity. While battery-electric vehicles have grown a lot recently, they are not new.

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Experiments on the development of the concept of electric vehicles can be dated back as far as 1828 by Jedlik Ányos, but a rechargeable EV didn't arrive until 1881 by the engineer and inventor Gustave Trouvé after the invention of practical secondary batteries [43]. By 1900, EVs started gaining attraction, and the number of EV manufacturers and models began increasing. In 1912 there were 33,842 electric vehicles registered in the US, but that was their peak then, and soon after that, internal combustion engine vehicles took off [43]. BEV is powered by a battery and electric motor with plug-in charging. Fuel cell electric vehicle (FCEV) is powered by a fuel cell connected with a hydrogen cylinder and supplied with oxygen from the air. At the same time, a plug-in hybrid EV (PHEV) is powered by a battery and electric motor with plug-in charging integrated with a conventional gasoline engine, as shown in Fig. 1.

Recent reports have shown how fast EVs have grown over the past few years. According to the global EV outlook prepared by the international energy agency, battery-electric and plug-in hybrid electric vehicle sales reached 2.1 million cars globally. Barriers preventing electric vehicles adaptation are mainly the replacement cost of batteries, and spare parts ranked at the top [44]. Electric vehicle sales have increased rapidly in recent years. Fig. 2 shows the annual global sales of EV. EV sales have experienced more than 70% growth from 2017 to 2018 and more than 120% increase between 2020 and 2021 [45]. Several automakers have stated an intention of reaching more than 15 million in electric car sales by 2025 [46,47]. This increase in electric vehicle sales will directly affect the decrease in battery prices over the next few years.

For instance, considering PHEV, excess power is injected into the grid when there are overload issues. These are key factors accelerating the development of EVs [48]. However, it must be noted that the dissipation of electrical energy for EVs is executed with the aid of power electronic converters and electric motor drives. These factors usually tend to impact the durability of the car positively. Usually, a maximum of 12 V or less is needed for a traditional internal combustion engine to start and run the vehicle, coupled with other auxiliary equipment [49]. Hydraulic systems in conventional vehicles made up of braking and other mechanical components are replaced with electrical systems in EVs, making them more convenient and easier to use and ensuring the user is well protected. As it is clear from Fig. 2 that BEV is the most commercialized type. One of the technologies appeared with the growth number of EVs is vehicle to grid (V2G). Vehicle to grid is a technology of connecting the EV to the grid to use the EVs battery packs as a power source to feed the grid when needed. This technology aims to use the growing number of EVs to help support the grid in terms of providing peak load shaving services that help reduce the load on the grid at peak demand time [50]. Verta (European electric vehicle charging platform) is starting to implement these types of charging stations [51]. Another recently revealed example from a car manufacturer is the new Ford F-150 lightning electric pickup truck, which features V2G technology. With the installation of a bidirectional charger, you can use the energy stored in the battery to power up your house during an energy outage and possibly send energy to the grid if needed [52].

Extensive work has been done to summarise the progress done in the batteries concerning electric vehicles, such as the safety issues in Li-ion batteries [53–55], improvement in Li-ion batteries in EVs [56], wireless charging of EVs [57], lifetime of batteries in EVs [58], and different thermal management systems in EVs [59,60]. However, the EVs' SWOT (strengths, weaknesses, opportunities, and threats) analysis has not been done yet. This work introduces a brief background about the recent progress of suitable batteries for EVs, the progress done in the different types of EVs, and Power Electronic Converters. Then the strengths (S), weaknesses (W), opportunities (O), and threats (T) of EV are introduced. Moreover, SWOT analysis of the battery electric vehicles (BEV) and their prospects in the automotive industry are presented. The next section (Section 2) of the study presents an overview of development in batteries for electric vehicles. Section 3 summarizes the various types of electric vehicles and this is followed by Section 4, which captures detailed discussion in relation to power electronic converters in electric vehicles. Section 5 touches on the Strength, Weakness, Opportunities and Threat (SWOT) for EV's. Section 6 presents a summary of the SWOT analysis of battery application in the automotive industry.

2. Recent development in batteries suitable for EV applications

In recent years, the push toward electric vehicles has increased the rate of development of electric cars significantly in all aspects, and the energy storage system is at the core of this. Among the different electric vehicles, the battery electric vehicle (BEV) is the most common and commercialized one. The development of BEV is directly related to the progress made in the battery sector. Different batteries are assorted into primary and secondary batteries. The primary ones are disposable or single-use batteries such as lithium metal alkaline. In contrast, the secondary ones are multi-use or chargeable batteries such as lead-acid batteries (LAB), lithium-ion batteries (LIBs), and nickel-metal hydride (NiMH) [61,62]. Commercially, the batteries are assorted according to the chemistry type, including lithium or nickel-based batteries, LABs, alkaline and mercury batteries, while in 2018, LABs, lithium-based and nickel-based batteries form 94.8% of the worldwide battery market [63]. Secondary batteries make up 73.8% of the global market of the battery, depending on chemistry type, from which LIBs and LABs form the majority (45.74% LIBs and 49.94% LABs). It is anticipated that soon, LIBs will make up more than 80% of the global secondary battery market [63,64]. LIBs are the most used batteries in electric vehicles today because of their advantages like high energy efficiency and high specific

Fig. 1. Different types of electric vehicles (EVs).

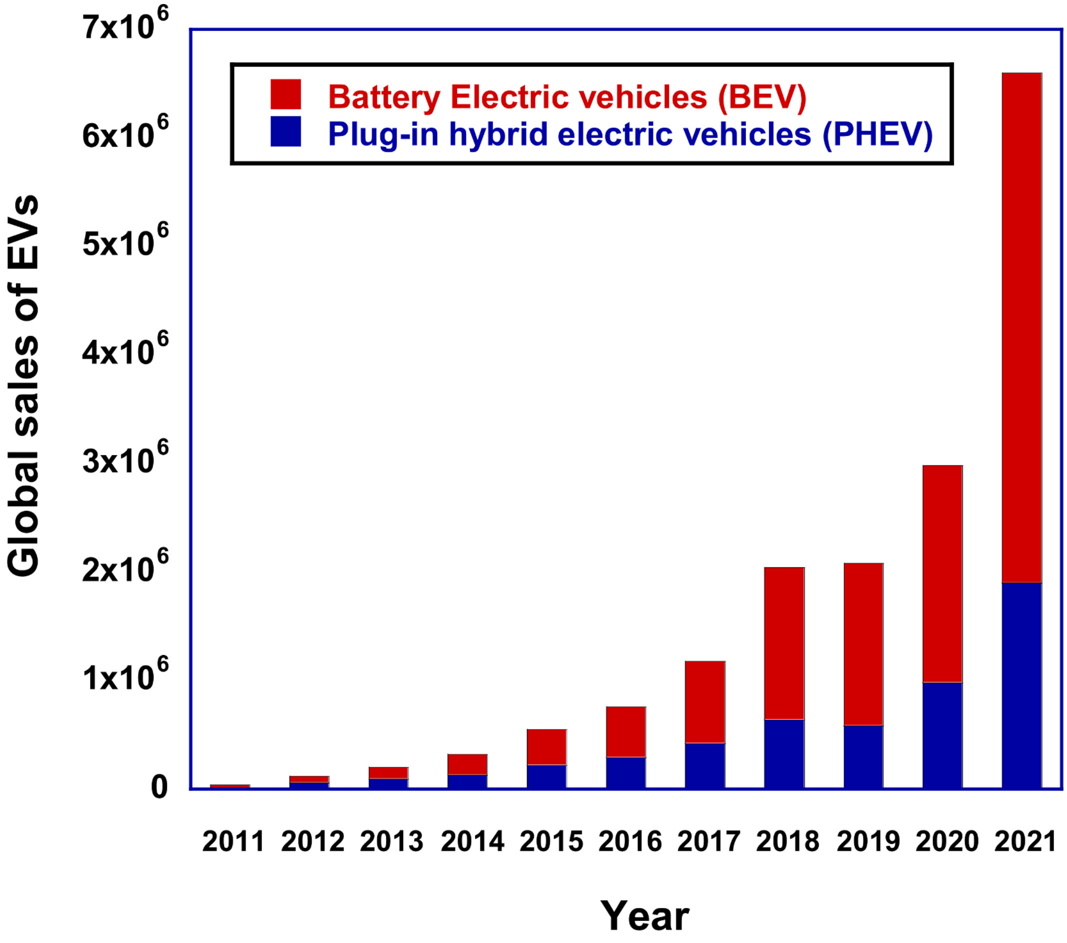


Fig. 2. Global sales of electric vehicles (BEV and PHEV) between 2011 and 2021 [45] (open access).

energy [60,65,66].

2.1. . Progress done to develop high-performance cathode of LIBs

In pursuit of higher energy density batteries for longer-range electric cars, significant research has been made to improve the electrochemical performance of LIBs. One of these areas of research is the cathode of Li-ion batteries. There are several commercial cathodes available such as Lithium cobalt oxide ($LiCoO_2$), Lithium iron phosphate ($LiFePO_4$), Lithium manganese oxide ($LiMn_2O_4$), and ternary-layered oxides such as lithium nickel manganese cobalt oxide ($LiNixMnyCozO_2$ (NMC)) and Lithium nickel cobalt aluminium oxide ($LiNixCoyAlzO_2$ (NCA)) [67]. One of the biggest bottlenecks of lithium-ion batteries is the relatively low capacity of its cathode material (under 250 mAh/g). Thus, significant research has been done to improve it, knowing that the theoretical energy density of these cathode materials is around 1000 Wh/kg. Fig. 3, shows these cathode materials' production and market share [67–69].

Lithium cobalt batteries (LCO) have been widely successful in

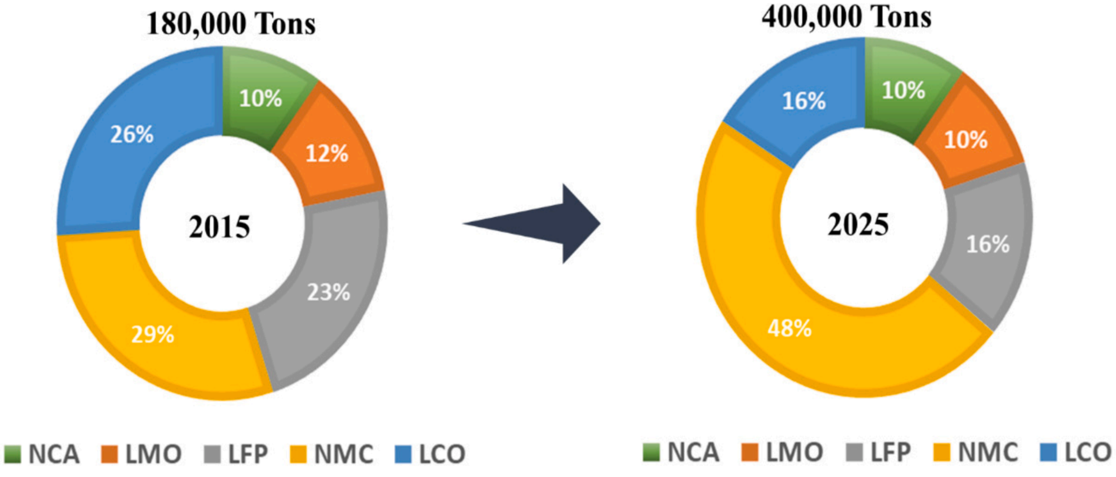


Fig. 3. Total production and market share of different cathode materials of LIBs (LFP: $LiFePO_4$, LCO: $LiCoO_2$, NMC: $LiNixMnyCozO_2$, NCA: $LiNixCoyAlzO_2$, LMO: $LiMn_2O_4$ adapted from [69] (Open access).

portable electronics due to their high volumetric energy density. They also power electric cars such as the Tesla roadster and the Smart ForTwo. Still, the high cost due to the limited cobalt resources has been a major limiting factor in its widespread adoption in electric vehicles [65]. Another cathode material used in electric vehicles such as electric buses in China is Lithium iron phosphate (LFP) [67]. The main advantages of using LFP batteries are their stable voltage, high cycling, and thermal stability [67]. However, moisture significantly affects the lifetime of LFP batteries [67]. Lithium manganese oxide (LMO) is another cathode material that is commercially used because it offers good thermal stability and rate performance at a low cost. However, low energy density means that LMO cannot be used alone as a cathode in electric cars and it is usually blended with Nickel manganese cobalt oxide (NMC) to improve its energy density. Nissan Leaf, BMW i3, and Chevrolet Bolt are examples of cars that use LMO—NMC batteries [65,67]. The most popular cathode materials for electric vehicles are Ternary layered oxides; specifically nickel-rich ternary layered oxides (NMC and NCA). Nickel-rich NMC provides higher capacity but suffers in thermal stability and cyclic performance, which is solved by preparing a full concentration gradient solution (FCG) [67]. Ni-rich NCA is also similar to Ni-rich NMC in providing higher specific energy, but it is not as safe, requiring additional safety measures before being integrated into electric vehicles; NCA is used in electric vehicles such as Tesla [65,67]. Fig. 4 shows a comparison between different types of lithium-ion batteries.

2.2. Progress done to develop high-performance anode of LIBs

Another area of research is the anode of LIBs. There are three main types of anode material insertion, alloying and conversion-based materials. Graphite and amorphous carbon are the most popular types of anode materials from insertion-based anodes [67,68]. Li-metal is also an anode material that might significantly affect the future of Lithium-ion batteries. Lithium metal batteries' high theoretical energy capacity of 3860 mAh/g and low working potential make it one of the majorly promising advancements in battery technology. However, before it is feasible for use, many problems need to be overcome, such as Li dendrites, low coulombic efficiency, and severe safety hazards [67]. The battery pack is the heart and soul of an electric vehicle. It consists of three levels: a cell, a module, and a pack. Battery packs also include the battery management system (BMS) and the thermal management system. A cell is a single electrochemical unit that can be connected in series or parallel depending on what is needed to form a module, each module gets its own battery management system, so the number of cells in a module depends on the module level BMS. Modules are connected in series or in parallel to form a battery pack. Finally, the battery pack is housed in a metal or plastic container that contains the pack's battery management system and thermal management system. The battery pack design has seen significant developments in recent years that enable storing more energy and increasing the driving range while keeping the pack relatively compact [65,70]. One of the recent developments in battery technology is Tesla's recently announced tabless batteries. Tabs are the current collectors in batteries, in cylindrical lithium-ion batteries, the electrodes are spiral in what is referred to as a "jelly-roll". This configuration has some inherent disadvantages, such as the lack of heterogeneity in current distribution and ohmic losses due to the length of electrodes which could cause temperature problems [71]. The new batteries proposed by Tesla use an array of current collectors at the edge of the current collector foil. This helps in more homogenous current distribution and lower temperatures due to the lower ohmic losses resulting from the shorter distance travelled by the electrons to the current collectors [71,72]. This new design results in five times less energy loss as heat due to ohmic losses than conventional batteries [71].

3. Electric vehicles

3.1. Battery electric vehicles

BEVs are described as 'purely electric vehicles' as the powertrain consists of a battery that can be recharged. These types of batteries are environmentally friendly compared to conventional energy conversion systems. In recent times, significant concerns have been raised about the batteries' manufacturing and how they are depleted during their end of life [73]. Charging these batteries is conducted using grid power or from any power generation medium using a charging plug [74]**.** The charging process for battery electric vehicles takes a bit longer, unlike conventional internal combustion engines. Using a slower charger could take 5 – 10 h to fully charge the battery, while a fast charger might take around 15 – 45 min, which is slower than ICE's [75]**.** Fig. 5 captures the power train for a battery electric vehicle (BEV). Thermal management and battery capacity are primary issues that affect the overall performance of

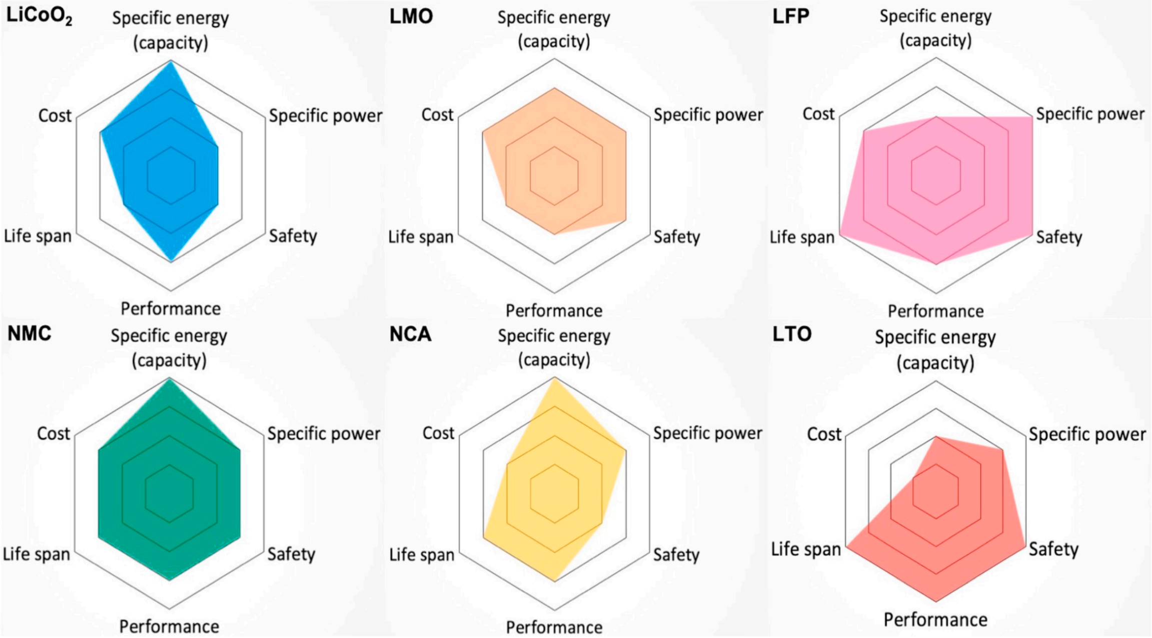


Fig. 4. Comparison between different types of lithium ion batteries used in electric vehicles (the outer hexagon is the most wanted) [56] (Open access).

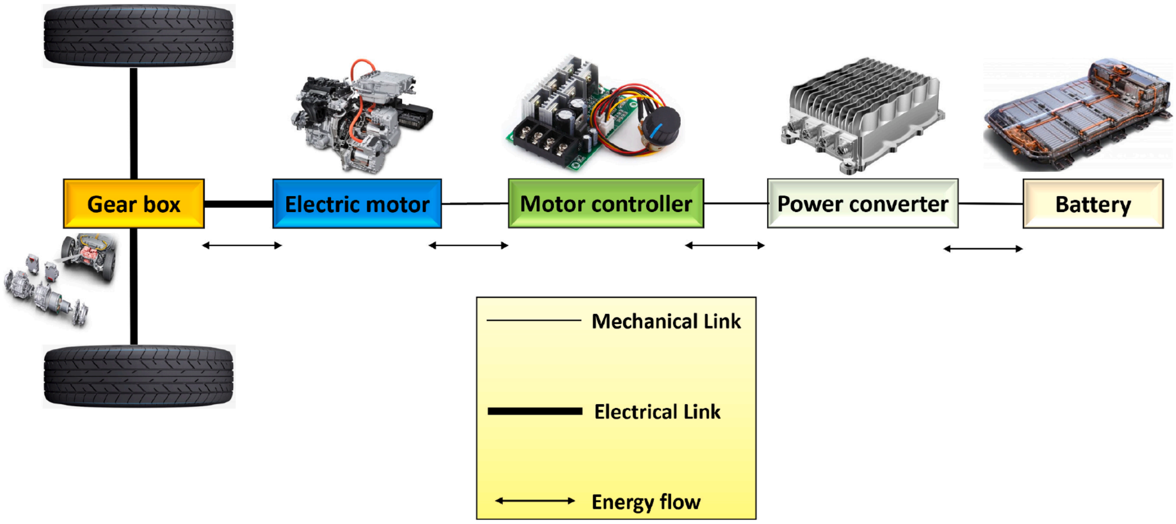


Fig. 5. Battery electric vehicle powertrain.

the battery-electric vehicle. The battery's operating temperature determines its longevity and performance [75,76]. These powertrains support the transition from electrical to mechanical energy with nearly no losses [68]. The driving range for BEVs is between 100 and 400 km, subject to the battery's capacity on the powertrain. The time required to charge the battery entirely depends on the battery capacity, charging scheme, and the type of connection used (parallel/series). To increase the travelling distance, hybrid electric vehicles were recommended by several research groups [77–80].

3.2. Hybrid electric vehicle

The hybrid electric vehicle means merging various types of technologies; hence two or more energy units are required to propel the drive train. Some energy sources are usually from flywheel, battery, and regenerative braking. Some models of hybrid electric vehicles derive their power from supercapacitors, electrochemical energy storage units like fuel cells and internal combustion engines. Using a fuel cell and ultracapacitor hybrid vehicles, 96.2% power efficiency can be attained at a speed of 158 km/h [81]. The total distance covered was also 435 km, with a total weight of 1880 kg. The mileage for the vehicle depends on the energy management of the entire system [82]. What makes the hybrid vehicle advantageous is that during cruising, when the fuel runs out, the secondary energy storage serves as a secondary option to mitigate the issue. There are series, parallel and dual hybrid electric vehicles based on the energy sources.

3.2.1. Series hybrid electric vehicles

For this power train, the power required to propel the vehicle comes from the electric motor and the internal combustion engines. A generator transforms mechanical power from internal combustion engines into electrical energy. Conversion of the AC to DC mainly to charge the batteries occurs with the aid of a rectifier (AC – DC rectifier) [83]. The internal combustion engine is not linked to the traction motor directly. Subject to other components in the drivetrain, a battery is placed between the internal combustion engines and the motor. The series hybrid

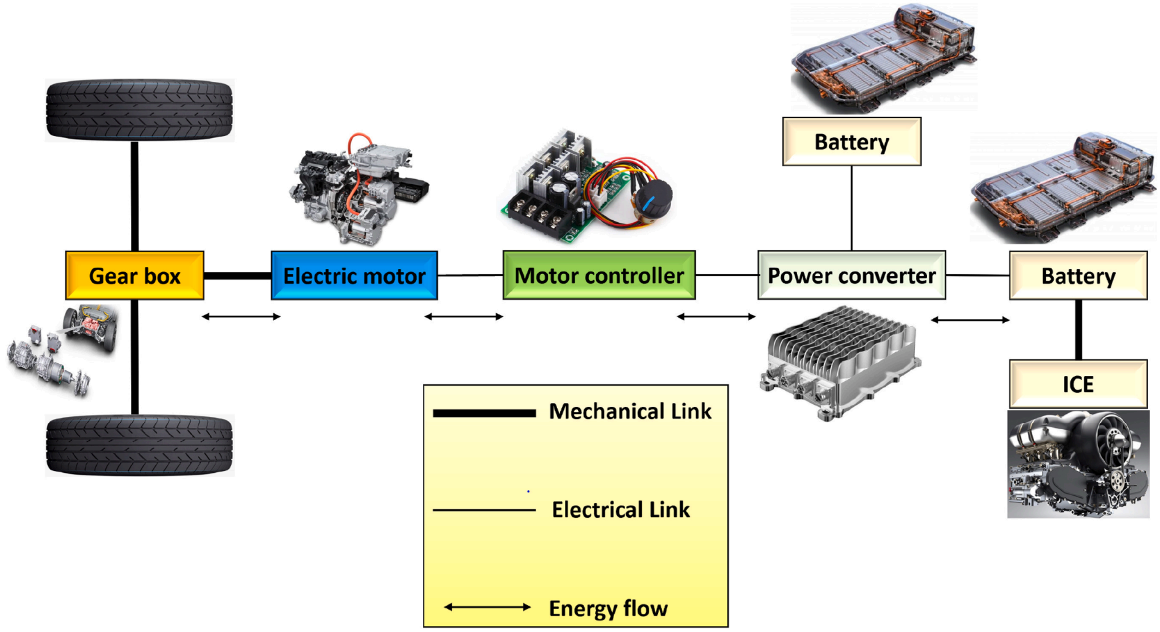


Fig. 6. Series hybrid electric vehicle.

electric vehicle comes with an internal combustion engine, motor and a generation. Mechanical energy is produced using internal combustion engines, but this generated mechanical energy is later transformed into electrical energy for driving the powertrain. In terms of efficiency, the series hybrid electric vehicle has lower performance than other vehicle drivetrains [84,85]. Fig. 6 shows the drivetrain for the series hybrid electric vehicle. The battery is charged as a result of the generator being propelled at ideal speed from the internal combustion engines. The system is designed so that when the battery's state of charge drops, the internal combustion engine charges the battery. When the battery attains its full charging capacity, the internal combustion engines disengage and stop charging the battery. However, it must be noted that the main power source for the drive train is the battery; hence, issues in the burning of fossil products are curbed.

3.2.2. *Parallel hybrid electric vehicle*

There is a parallel connection between the electric motor and the internal combustion engines to generate traction power, as shown in Fig. 7. The internal combustion engine functions as the system's primary energy for these drivetrains, while the motor serves as backup power. This approach aid in the fuel consumption of the drivetrain [86]. The key benefit of using this drive train is that a small battery backup is needed, which reduces the vehicle's operating cost. Charging the batteries is also due to regenerative breaking while the vehicle is in motion. It has been investigated that using this drivetrain increases the fuel economy by 68%, while there is decrement of 40% in terms of releasing harmful gases into the atmosphere. The engine's efficiency also increases by 6% on a real-world – drive cycle.

3.2.3. *Dual hybrid electric vehicle*

Another name for the dual hybrid electric vehicle is the series-parallel EV because of the combination of the series and parallel drivelines depicted in Fig. 8. They usually come in as a powertrain with two structures [87]. The first part is an internal combustion engine coupled to a generator with the aid of a gear assembly unit. The second is an electric unit composed of a generator, motor, and battery. Some academic content describes this power train as power-split transmission because it can sustain and deliver varying velocities at the optimum operating speed of the engine. These types are operational in both series and parallel modes [88]. These systems are very complex and expensive; however, they are often preferred compared to other structures despite the fact that battery electric vehicles are cheaper.

3.3. *Plug-in hybrid electric vehicle (PHEV)*

The gasoline is used for longer journeys when the battery power runs out [89]. Fig. 9 shows the drive train for plug-in hybrid electric vehicles. The sole source of emissions for PHEVs and all-electric cars is energy; however, the power source, such as a power plant, may still emit some pollutants. All-electric cars and plug-in hybrid electric vehicles usually have lower emissions well to wheel than conventional vehicles powered by gasoline or diesel in locations where electricity is generated using relatively low-polluting energy sources. EVs may not significantly reduce well-to-wheel emissions in areas where coal is a primary energy source [90]. Table 1 shows a comparison among the different types of electric vehicles.

4. Power electronic converters in EVs

Converters are power electronic circuits capable of converting voltage and current into others with different amplitudes and/or frequencies, also responsible for managing the quality and flow of available energy. The converter applied to the traction system must have the ability to operate with a bidirectional flow of energy, where energy can flow from energy accumulators and/or sources to the traction motor or from the traction motor to the accumulators during braking [91]. In addition to the converter driving the energy flow between the traction motor and the vehicle's electrical system enables the interconnection between different voltage levels and energy sources onboard the vehicle. The choice of converter type depends on the function to be performed by it. The topologies of energy converters applied to systems can be divided according to the type of conversion (AC-DC, DC-DC and AC-AC), connection method (cascade or integrated) and power flow (unidirectional or bidirectional) [92]. Some of the power electronics converters types are shown in Fig. 10.

For all electric vehicles, the energy from the supercapacitor or battery, and fuel cell is used to propel the vehicle and every other onboard components [93]. When the vehicle is being driven in fuel mode, the

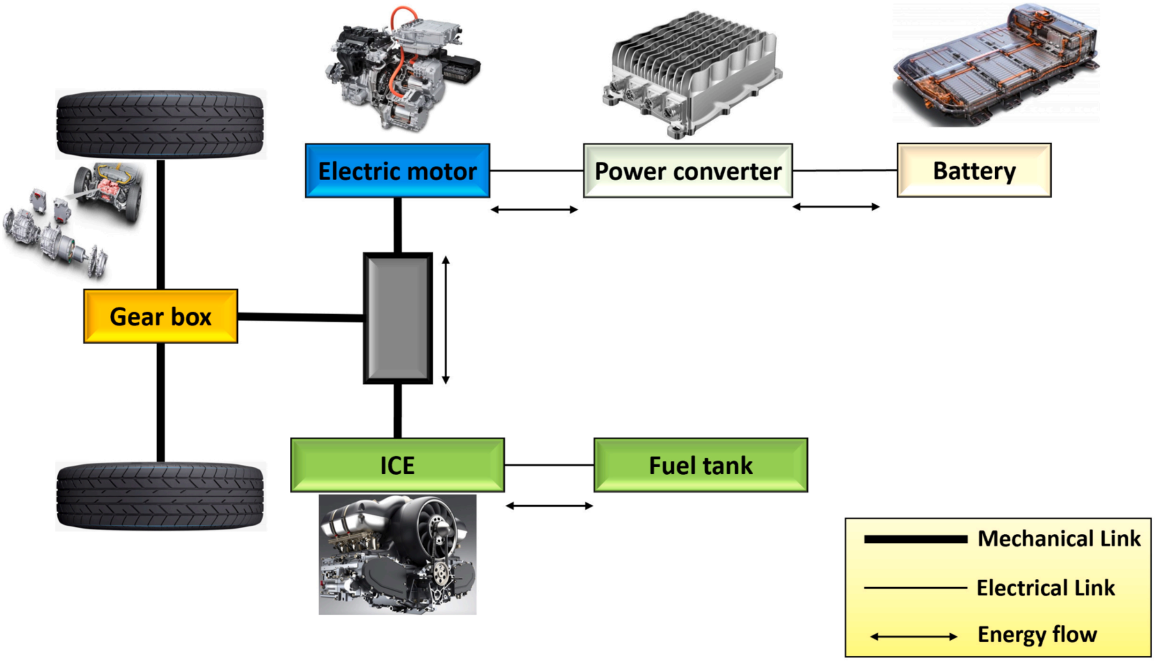


Fig. 7. Parallel hybrid electric vehicle.

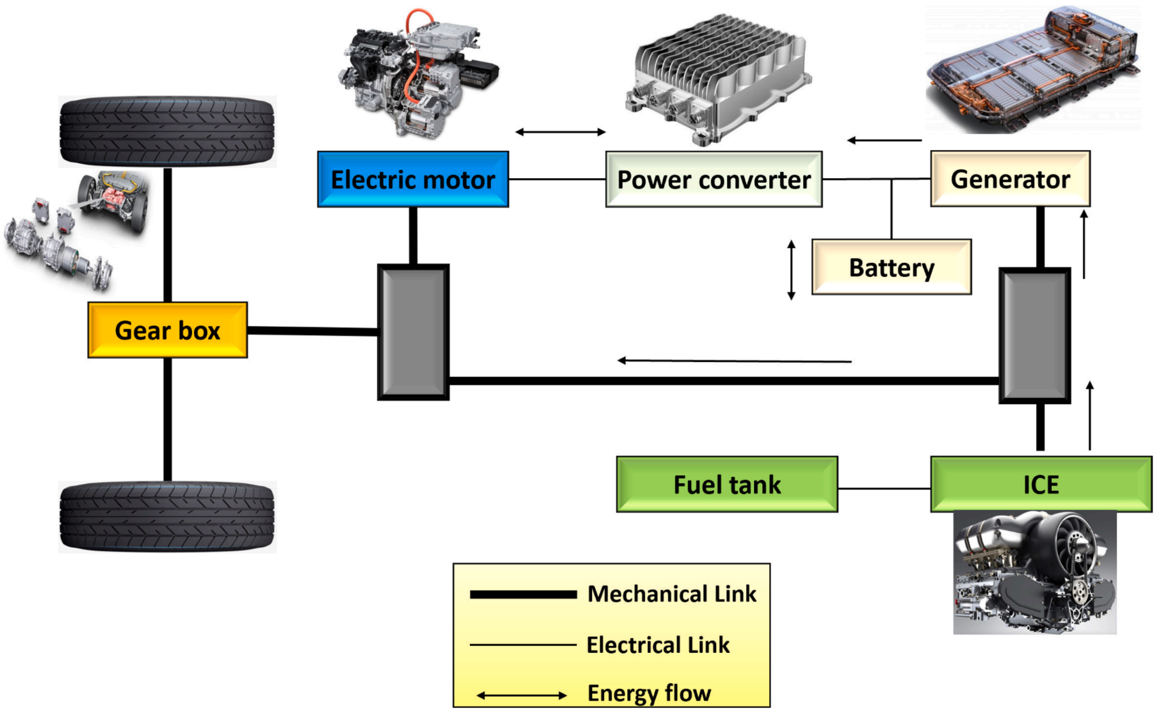


Fig. 8. Dual hybrid electric vehicle.

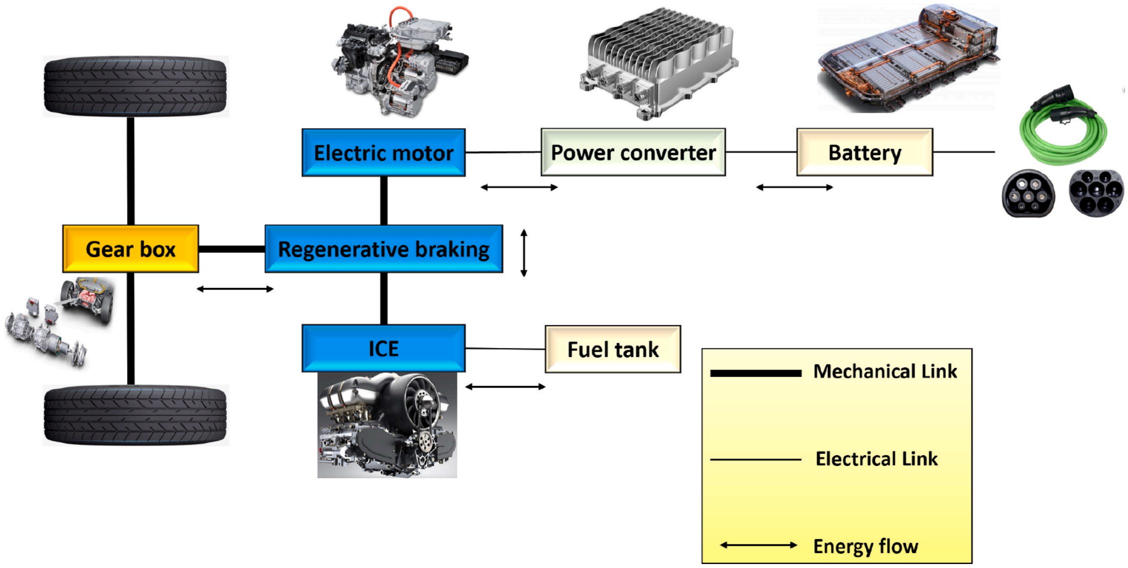


Fig. 9. Plug-in electric vehicle.

voltage generated is not capable of propelling the car; hence it is usually supported using a unidirectional boost converter [94]. The vehicles come with several electronic loads to enhance the user's comfort. Some of these loads demand a higher alternating current, such as the air conditioner, which is usually obtained from a DC-DC converter. The load requirement for various components in the car occurs at varying voltage ratings [95]. For instance, the projector and interior lamps require 42 V and 12 V, respectively. Other loads, like sensors, communicating devices, etc., demand lower voltages under various operating conditions. The demand needed in terms of voltage tends to alter as the electrical load changes, and it's usually impossible to derive this energy from a single source like a battery. It, therefore, becomes necessary that the DC-DC converters increase for varying rated loads, which has a ripple effect on the battery's performance in a vehicle. There are two structures commonly used in a vehicular system; the first is a vehicular system operational with an internal combustion engine or fuel cell having a single battery, and the second is the utilization of multiple batteries, often 14 and 12 V rating. For the double battery system, a dual voltage is obtained from a generator in a hybrid electric vehicle, sometimes from the grid, depending on the type of EV in question. A 36 Vs battery is required for mid voltage purposes as well as 12 Vs battery is demanded for lower voltage purposes. These batteries are then boosted to 42 Vs drive and higher voltage purposes. The battery is charged with the help of the voltage deduced from the generator using a rectifier as well as a unidirectional DC-DC converter for series hybrid electric vehicles and series-parallel hybrid electric vehicles [96]. The voltage, in some cases,

Table 1
Summary of comparison between the various types of electric vehicles.

Electric vehicles	Hybrid electric vehicle	Plug-in hybrid vehicle	Mild hybrid vehicle
No IC engine Only electric drive Battery pack size is large (20–80 kWh) Example: Nissan Leaf, Tesla Model S Sub-category REEV (Range Extended Electric Vehicle) like BMW i3	Has IC engine and electric motor The batteries get charged by the engine Battery pack size is medium (6–12 kWh) Example: Honda Civic Hybrid	Has IC engine and electric motor The batteries can be charged from an external source (plug) Battery pack size is medium (6–12 kWh) Example: BMW i-8	IC engine and electric motor Turns off the engine and switches to motor when coasting, braking and restarting quickly Cannot be solely driven on electric motor Example: Chevrolet Silverado Hybrid

is supplied to higher voltage applications and transformed into variable frequency using 3 phase inverter. Energy is wasted when the car is decelerating, braking or charging the batteries. The 3-phase converter is transformed into a 3-phase rectifier in this case. The rectified output is changed to a battery voltage using a bidirectional DC – DC converter [97]. For the cars being developed lately, the 3-phase converter functions as an inverter when the vehicle is in fuel, battery, split and combine mode or as a rectifier when in regenerative mode. The traction controller system is designed to carry out this task. It basically produces pulses for the 3 phase converter subject to the signal received from the traction motor and the vehicle drivers. The 3 phase converter's operating characteristics are either an inverter or rectifier based on the controlled pulse. This voltage unit manages the state of charge for the battery at the minimum and maximum level. The controller detects the state of charge level for the battery and compares that to a reference voltage signal. Fig. 11 captures the various categories of power electronic converters. Bidirectional converters are very common types of converting units in electric vehicles. There function as both boost and buck converters in order to increase the voltage from low to high or high to low, respectively [98].

Bi-directional power flow also incorporates single input, multi-input, and multistage converters coupled with multiphase non – isolated converters. Other authors have equally explored buck-boost bidirectional converters for electric vehicles, as captured in Fig. 12 [99]. The bidirectional Buck-Boost converter can work with an output voltage lower than, equal to or higher than the input. The flexibility in the system is obtained due to a merge system between the Buck and Boost converters, as this system works with the combination of a Buck input feature and a Boost output feature. A speciality of this converter is that it has an inverted polarity compared to the input voltage. Both the input and the output have voltage source properties [50,51] for this converter.

The topologies of bidirectional converters most used to charge and discharge the batteries of the traction system on board the vehicle are the Buck, Boost type topologies, represented by Fig. 13(a), converter full-bridge (b), and multiphase type (Multiphase Interleaved converter) such as the converter in Fig. 13(c) which also has the inductors coupled. Half-bridge topologies (Fig. 13(d)) and Push-pull (Fig. 13(e)) are also used, but to process lower powers [100–104].

The converter illustrated in Fig. 13(a), presents the configuration of the input current divider (Multiphase Interleaved) or even double Boost (through inductors L1 and L2) with isolation using a transformer between input and output. It is possible to apply voltage gain in the boost stage and also in the transformer to obtain high voltage at the output to low voltage at the input, but a switch always needs to be conducted to provide a path for the inductor's currents, and it also has fewer semiconductors than the structure of Fig. 13(b) [102,103]. These converters generally raise the battery bank voltage to the DC link levels where the traction converter and other higher power loads are connected. They can adapt voltage levels on the battery bank side, ranging from 100 to 400 V, and on the DC bus side, ranging from 100 to 800 V, as well as average processing powers in the range of 10 kW – 50 kW, and must have high yield (> 97%) [105].

4.1. Single-phase voltage DC-AC inverter

DC-AC inverter can transform a continuous waveform into an alternating waveform, usually in a square or PWM-modulated waveform.

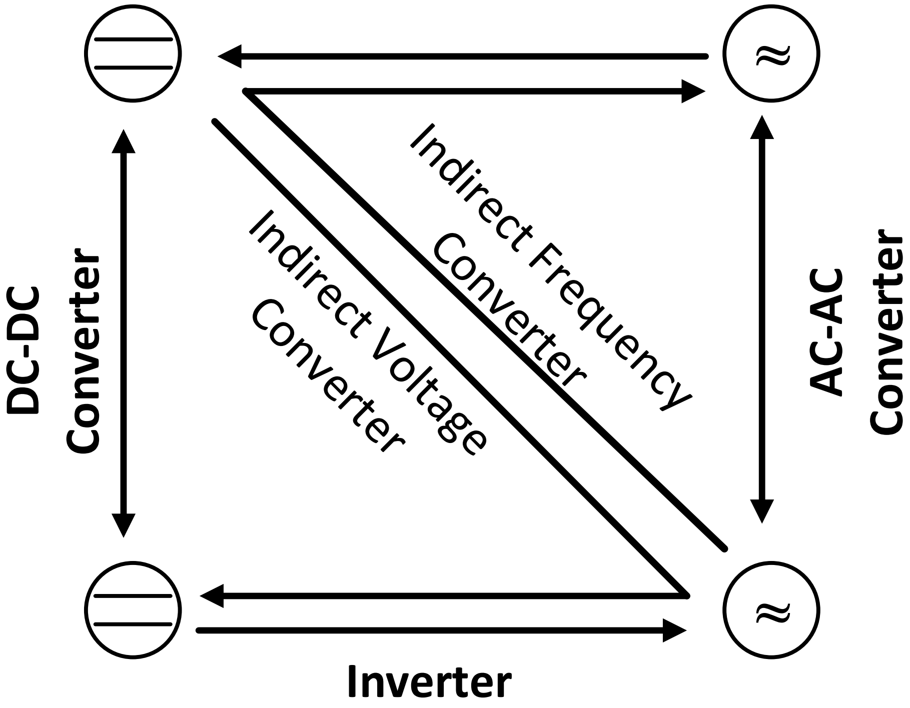


Fig. 10. Principles of power electronics converter.

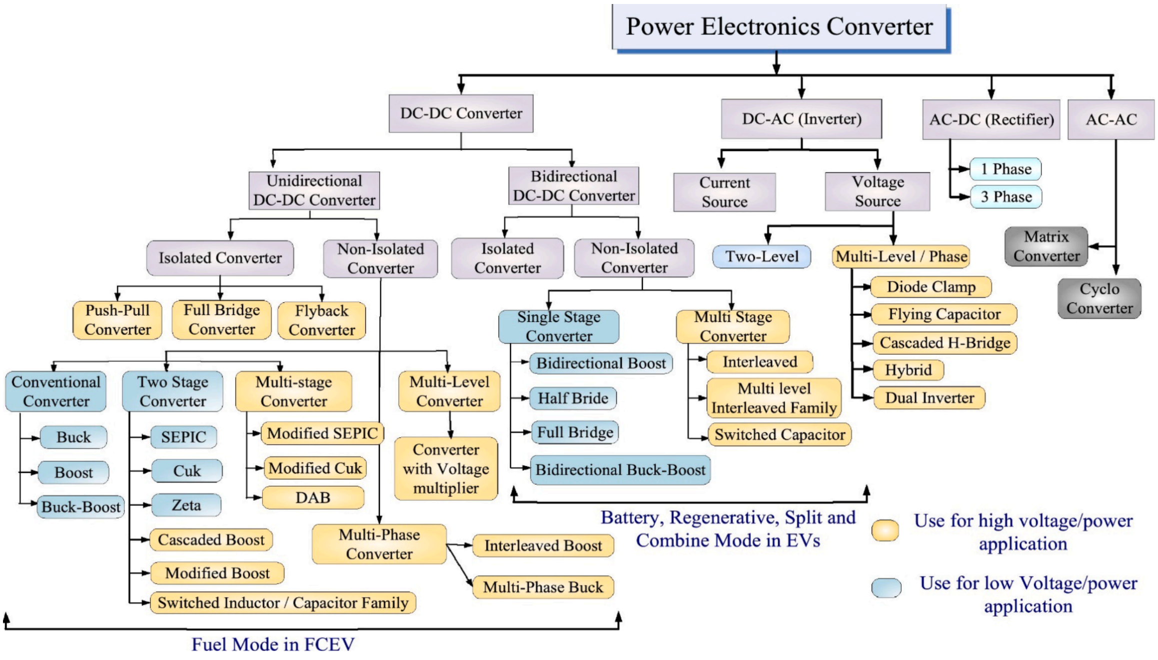


Fig. 11. Various classifications of power electronic converters [76] (Open access).

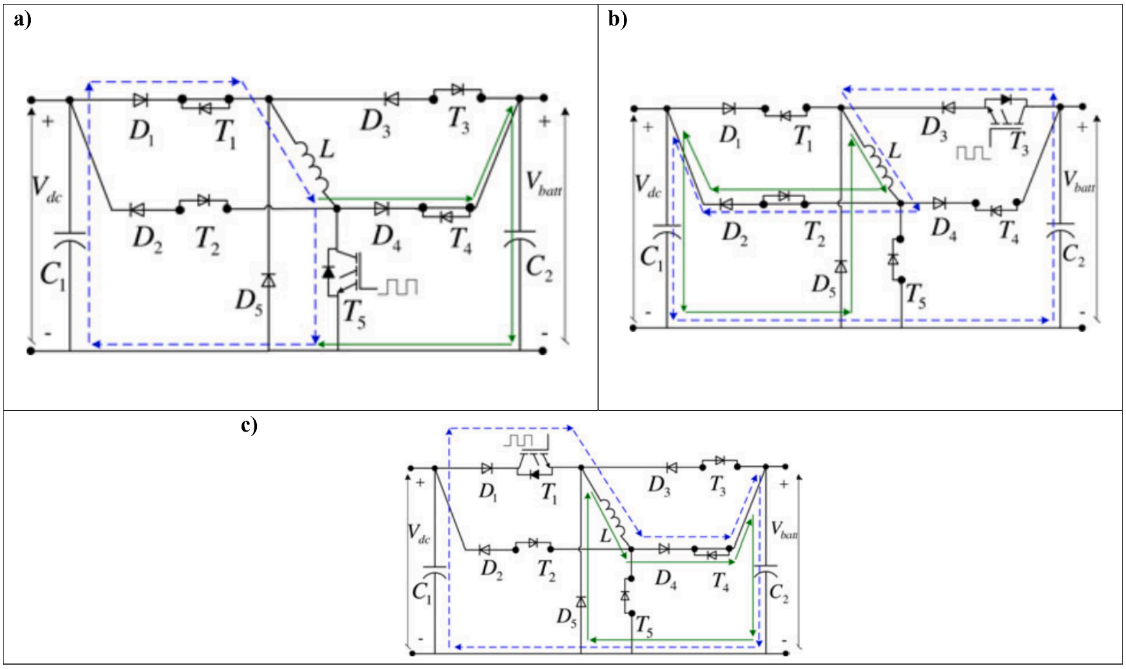


Fig. 12. Universal bidirectional converter a) $V_{dc}toV_{batt}$ boost mode of operation b) $V_{batt}toV_{dc}$ buck operating mode c) $V_{dc}toV_{batt}$ buck operating mode [98] (Open access).

Among the various topologies found in the literature, the most common are the DC-AC voltage converters presented below.

4.1.1. *The full-bridge single phase inverter*

This structure is recommended for high-power inverters and high output voltages. The output produced is a sinusoidal voltage resulting from this inverter combined with an appropriate modulation and filter technique [106,107]. The single-phase full bridge voltage inverter is shown in Fig. 14. It comprises two arms: one arm of the inverter is made up of switches S1 and S4, and the other is made up of switches S2 and S3. The semiconductor switches are activated in diagonal pairs; it is done in a complementary way with a 180° phase shift. At the moment switches S1 and S4 are conducting, the output voltage applied to the load equals the input voltage (+Vin). When switches S2 and S3 are conducting, input voltage with reversed polarity is applied to the load (-Vin). Therefore, the result is a square waveform of magnitude equal to the input source (DC bus) [108].

4.1.2. *Half-bridge single-phase voltage inverter*

The half-bridge inverter is also known in the literature as the Mid-Point inverter or Half-Bridge (half-bridge) and can be seen in Fig. 15. This structure is the simplest and has only one arm with a single pair of

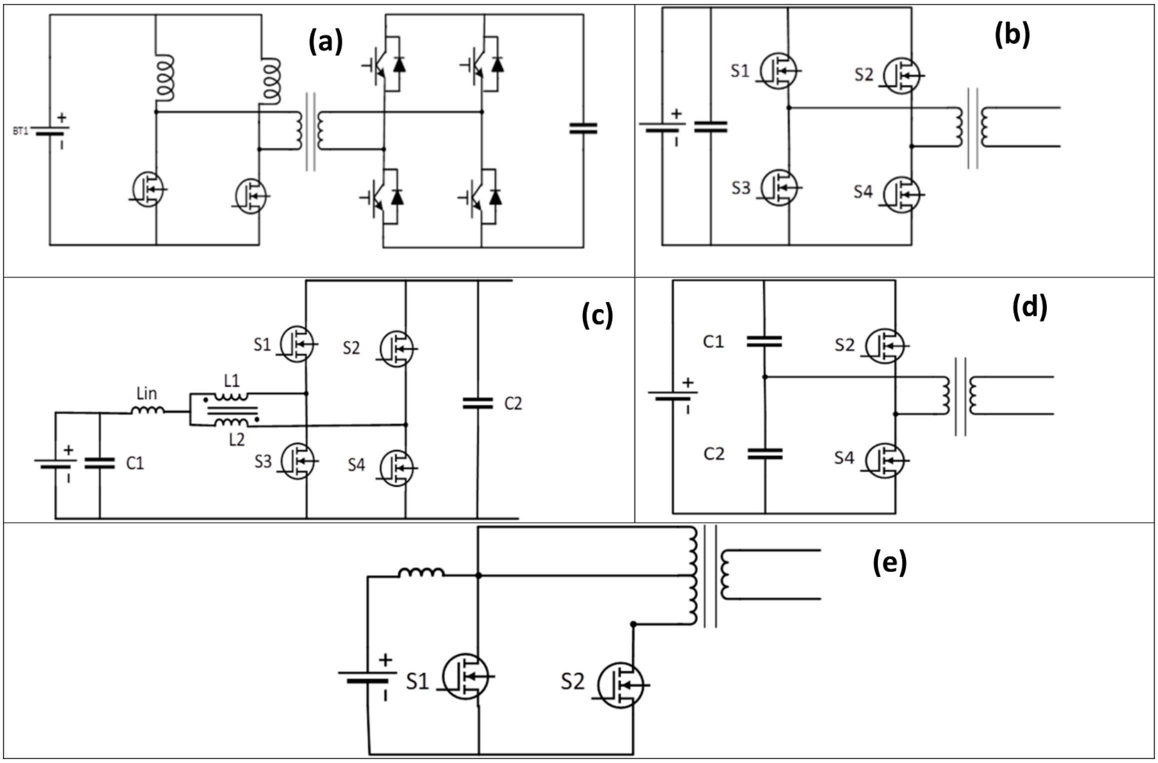


Fig. 13. Bidirectional DC-DC converters applied on board the EVs. (a) Isolated multiphase interleaved (b) Full-bridge, (c) Multiphase interleaved, (d) Half bridge, and (e) Push-pull.

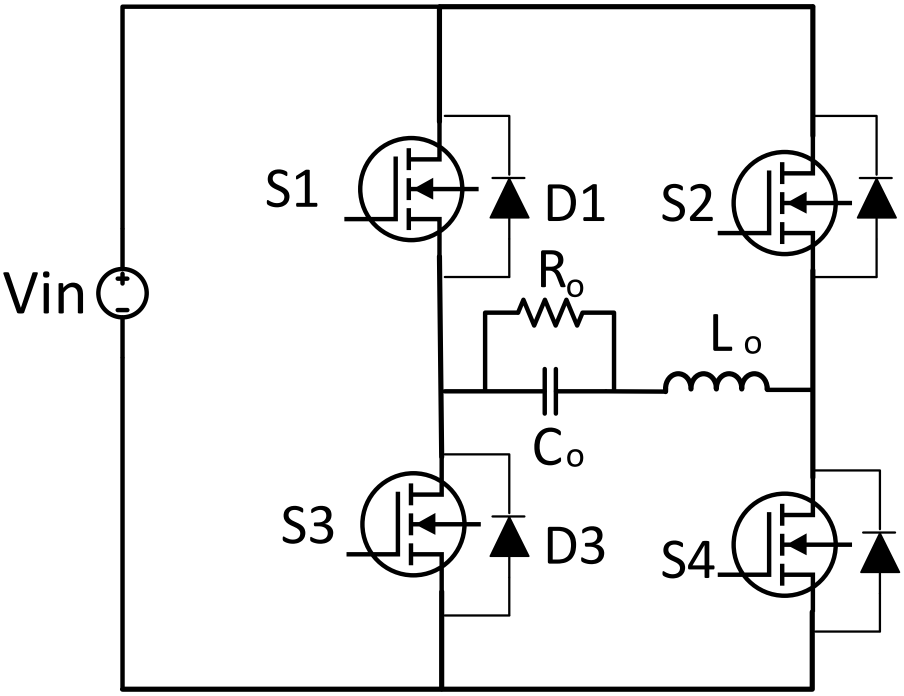


Fig. 14. Full-bridge DC-AC converter.

semiconductor switches and needs a midpoint DC power supply. This circuit is used in low-power applications because the voltage level at the load is half that applied by a full-bridge topology, resulting in a current twice as high for the same power [109].

Its operation can be described as follows: the semiconductor switch S1 is turned on, the current grows exponentially, and the power supply delivers energy to the load. When S1 is open, the load current is maintained in the same direction since the load inductance does not allow sudden changes in current, decreasing through the antiparallel diode D2. The current will circulate through the diode D2 until it is zero, causing the semiconductor switch S2 to start conducting. The current will reverse direction and grow exponentially from this moment on. In

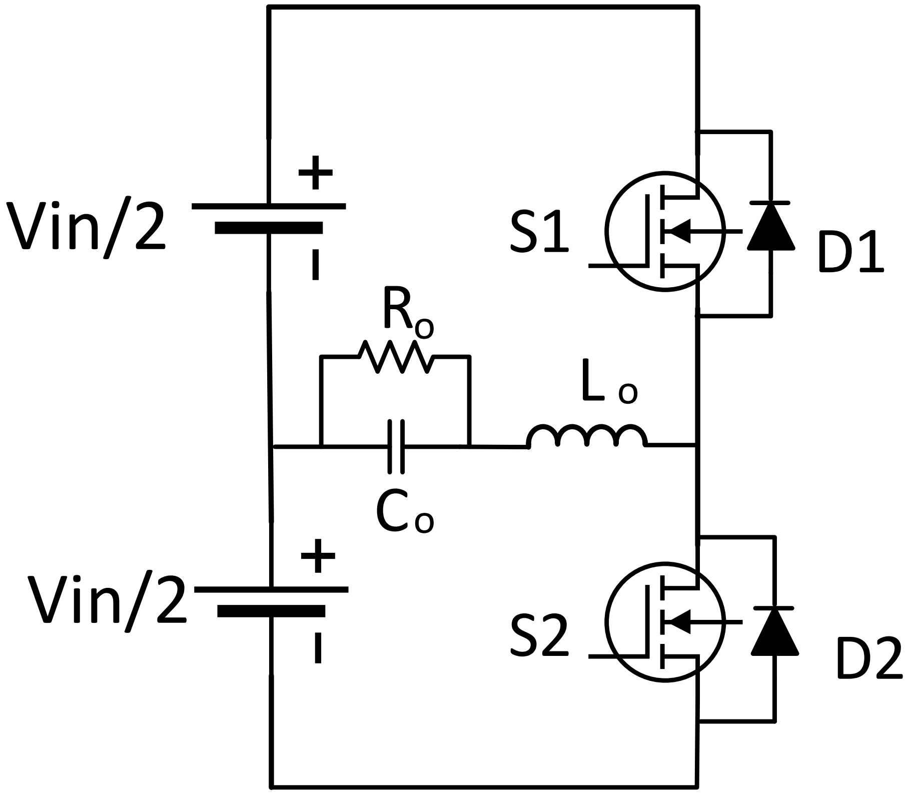


Fig. 15. Half-bridge DC-AC converter.

this step, the load receives energy from the source. And when the current cancels, it will restart a new cycle of operation [110].

It can be verified through the description of the operation of this topology that its switches S1 and S2 conduct or are blocked alternately, causing the output voltage applied to the load to be a square wave, whose frequency will be determined by the switching frequency.

4.1.3. Single-phase push-pull voltage inverter

The push-pull inverter configuration is well adapted to modulations at low frequencies and low powers. The configuration of this inverter can be seen in Fig. 16, and it has the following characteristics: it employs only one DC power supply (Vin), it employs only two commanded semiconductor switches (S1 and S2), the load is isolated from the DC power supply - naturally insulated structure employing a transformer with a midpoint in the primary, the DC power supply and the semiconductor switches are connected to the same reference [111].

When semiconductor switch S1 goes into conduction, S2 is kept locked. The load current grows significantly, and during this step, the power supply supplies power to the load. When opening S1, the current remains in the same direction due to the load inductance, so it starts to decrease through diode D2 [112]. With the cancellation of the current, another stage of operation begins. The semiconductor switch S2 is placed in conduction, and the current starts to grow again in the opposite direction. During this stage, the source transfers energy to the load again. When S2 is opened, the current will decrease through diode D1, and the energy stored in the load inductor will be transferred to the power supply. This stage ends when the load current is zero.

4.2. Main issues in the development of power electronics for the automotive industry

As discussed earlier, for electric vehicles, the mechanical coupled with the hydraulic share are substituted with an electric motor to support the movement of the drive train. Therefore, it is imperative that the ideal combination for the internal combustion engine coupled to the battery and fuel cell is selected to sustain the system's performance [113]. When the vehicle is driving in either the fuel cell or battery mode, power electronic converters perform a crucial role in enhancing the performance, but again it also comes with ensuring the best converters are selected. However, it comes to buttress the point that switching approach for the converters, selecting the power electronic converters, systemic integration coupled with how the individual units are aligned together contributes to the vehicle's overall performance in the automotive industry. Very often, these systems are chosen based on the input supply and the load demand. Performance of the converters in this case will be subject to the number of components incorporated, controlling strategies etc. Maintaining the charging and the discharging level of the battery using a voltage controller is another key factor in ensuring the vehicle's durability is maintained. Power electronic converter's durability is dependent on the semiconductor devices. Ideally, they must be capable of supporting higher vibrations coupled with unfavourable thermal scenarios. Again, to avert the situation, it is recommended that better converters having higher efficiency are selected. Issues pertaining to cost should be taken into account as well as the size of the unit. The power electronic converters are further required to sustain faster and higher power industrial motion control; hence today, these systems are merged into a digital sensor to increase the performance. In terms of safety issues, using power electronic converters coupled to digital signal processing units can ensure the traction motors are constantly monitored to determine defects associated with the stator, rotor, and bearing. Cost is also another major issue. An increment in the load demand due to user's preference is tantamount to an appreciable increase in cost.

High penetration of PEVs brings new challenges to operating systems due to an increase in peak energy demand. In this way, it is important to study both the challenges of the network load profiles and the penetration of PEVs to understand their impact on the daily load curves. The expansion of electric mobility will create charging profiles, which, if not economically regulated, will have impacts. These will be higher,

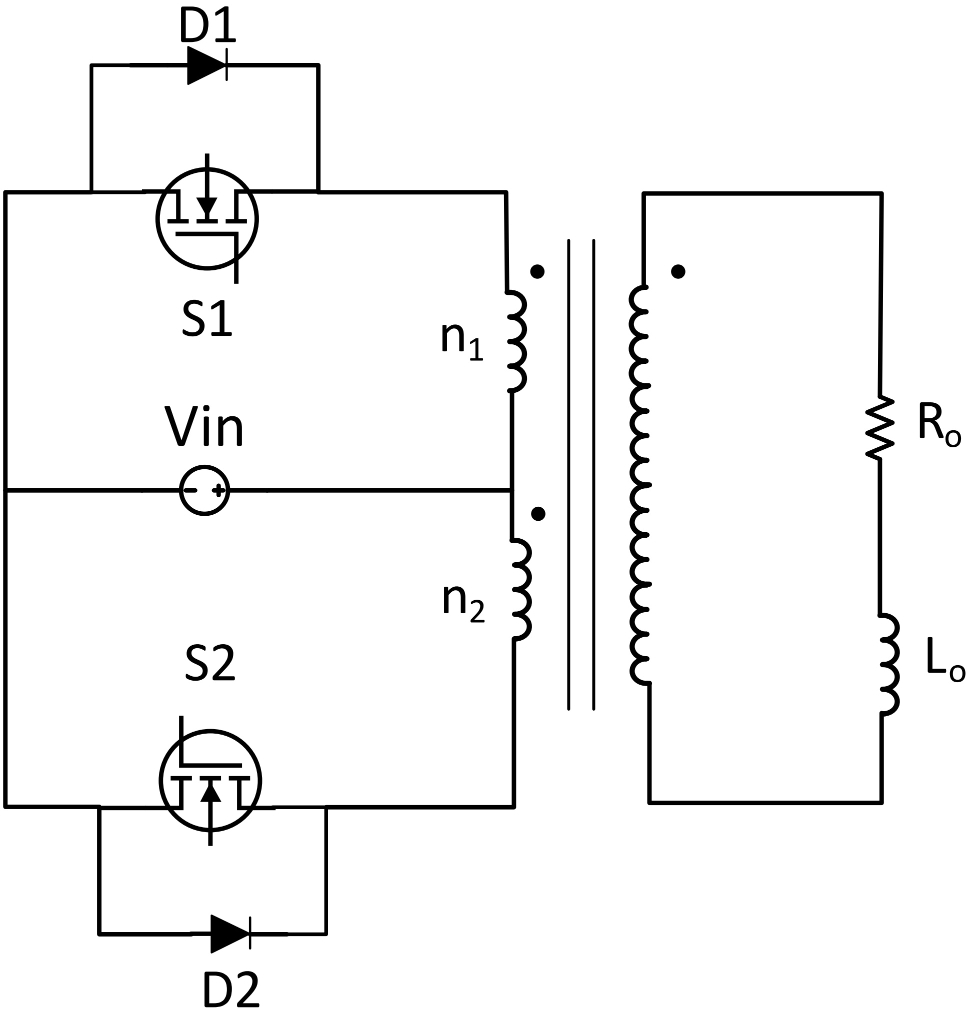


Fig. 16. Push-Pull DC-AC converter.

especially in the case of charging the EVs when the user arrives home. This type of loading will create various impacts such as increasing the daily peak of energy consumption, decreasing the reliability of the system, and finally expected insufficient electricity supply.

In this way, the control of the charging of electric vehicles through Demand Response strategies begins to have importance. Load Shifting and Valley-filling are loading strategies often touted as short-term solutions. To make this type of solution viable, it is necessary to create a decentralized approach to the problem, thus giving the user the power to choose the charging profile of the electric vehicle. Thus, charging the EV should be subject to regulated and dynamic tariffs, imposing more expensive energy prices at the time of greatest consumption to encourage the user to do so at the time of lower consumption.

5. Strength, weaknesses, opportunities and threats of the EVs

SWOT matrix has been applicable in several areas, mainly to determine a prudent analysis of a scenario [114]. The strength, one of the critical categories of the analysis, highlights the positive impact of the scenario compared to others, while the weakness is negative factors that lead to unfavourable scenarios. Opportunities are the external influence that can impact the scenario positively futuristically. The external impact that could alter the performance leading to insecurities is captured under insecurity [115]

5.1. Strengths of electric vehicles

One of the most significant advantages of electric vehicles is that they do not release any harmful emissions during their operation, which will help reduce greenhouse gas emissions from the transportation sector. The transportation sector is the most cost-effective method of reducing GHGs. This is supported by the continuous decline in EV costs and the approaching price parity between EVs and internal combustion engines [30]. Laberteaux and Hamza [116] studied the effect of using electric vehicles on GHG emissions. The study considers the driving patterns of 2910 vehicles from the California Household Travel Survey. It shows that using hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) instead of internal combustion engines reduces GHGs by up to 2 – 2.5 times as the driving style moves from least city-like driving to most city-like driving. As for fully electric vehicles, the reduction in GHGs increases, especially 3 to 6 times higher than HEVs and PHEVs, as the driving style becomes more and more like city driving [116].

Another paper studied the well-to-wheels (WTW), well – to – tank (WTT) and tank – to - wheel (TTW) CO_2 emissions of electric vehicles, including the emissions generated by power plants used to generate the electricity used to recharge the batteries [117]. This paper showed that in 2015 for the city of Beijing, because of the rapid switching from coal to natural gas power plants, using electric vehicles and plug-in hybrid electric vehicles reduced CO_2 emissions by 32% and 46%, respectively, compared with internal combustion engine vehicles (ICEVs) specifically multi-purpose fuel injection (MPFI) vehicles as seen in Fig. 17. Of course, achieving WTW emission reductions depends on each country's electricity grid power mix and the improvements made to the manufacturing processes; as long as the electricity generated by non-fossil fuels keeps increasing, the WTW CO_2 emissions will continue to decrease. The fact that EVs don't produce any emissions during their operation and their emissions mainly come from material mining and extraction and battery manufacturing processes which usually take place outside of cities. Thus EVs can help reduce pollutants in urban areas and contribute positively to human health [118].

Another notable feature of electric vehicles is their quiet operation due to the absence of mechanical noises. The quiet operation of EVs at lower speeds can cause a problem for pedestrians because they might not notice the vehicles approaching. Thus, EVs are being equipped with a system called Acoustic Vehicle Alerting System (AVAS), which emits a sound to warn nearby pedestrians. A study compares the noise levels of electric vehicles to those of internal combustion engines to see if EVs can positively impact noise levels. It is shown that free field traffic at speeds above 50 km/h, the effect of electric vehicles on noise levels is negligible due to the dominating influence of rolling noise, Fig. 18a. However, for urban areas at speeds below 50 km/h, electric vehicles positively affected noise levels and improved 10% of citizens or 6%, in case electric vehicles equipped with Acoustic Vehicle Alerting System (AVAS), Fig. 18b [119].

Incentives and policies that help push and increase the rate of electric vehicle adoption are other advantages of electric vehicles. Many countries worldwide have added incentives in the form of subsidies to help decrease the price of EVs. Norway is an excellent example of successfully using policies to increase the rate of electric vehicle adoption, 30% of new cars sold in Norway in 2016 were EVs [120]. Considering Norway's success in growing the EV market share, it is important to mention other incentives and policies they have implemented, such as free public car park parking, free battery recharging, and exemptions from public road tolls [120]. The United States offers a federal tax credit of up to $7500 on all new electric and plug-in hybrid electric vehicles, other than the incentives offered on state levels such as California's Electric Vehicle Rebate program, which offers up to $1500 for EVs with a minimum of 5 kWh battery [121,122].

Other advantages of electric vehicles include much faster acceleration and lower maintenance and operation costs [123]. Additionally, compared to ICEVs, electric vehicles have much greater energy efficiency. Most of the energy generated by the battery pack is converted and transferred to the wheels, resulting in the aforementioned fast acceleration [124].

5.2. Weaknesses of electric vehicles

One of the downsides of using Electric vehicles compared to internal combustion engines is a long time required to recharge their batteries [65]. Long recharge time coupled with the limited driving range of EVs add to the importance of having an adequate charging infrastructure to support the transition to electric vehicles. The relationship between the charging infrastructure and the number of EVs on the road can be referred to as the "chicken and egg" conundrum; developed charging infrastructure can be a factor that positively affects the rate of EV adoption, but investment in more charging stations depends on the number of EVs on the road [125]. Supporting the charging infrastructure can significantly affect the development of the EV market. The lack of adequate charging infrastructure can prevent users from transitioning to electric vehicles. Coupled with the charging infrastructure is the importance of having a centralized network of information about the available charging stations and their working status. It also improves the interoperability between the car and the different recharging stations and their billing systems. A fragmented network that doesn't show up-to-date information and requires various registrations and payment setups can negatively impact EV users and hinder the progress toward electric vehicles [120,126].

Additionally, the rollout of DC fast chargers must be supported to mitigate the effects of long recharge time for EVs. Electric vehicles can be recharged using standard plug sockets, but this takes a very long time; DC fast chargers reduce EV charging time significantly by requiring high

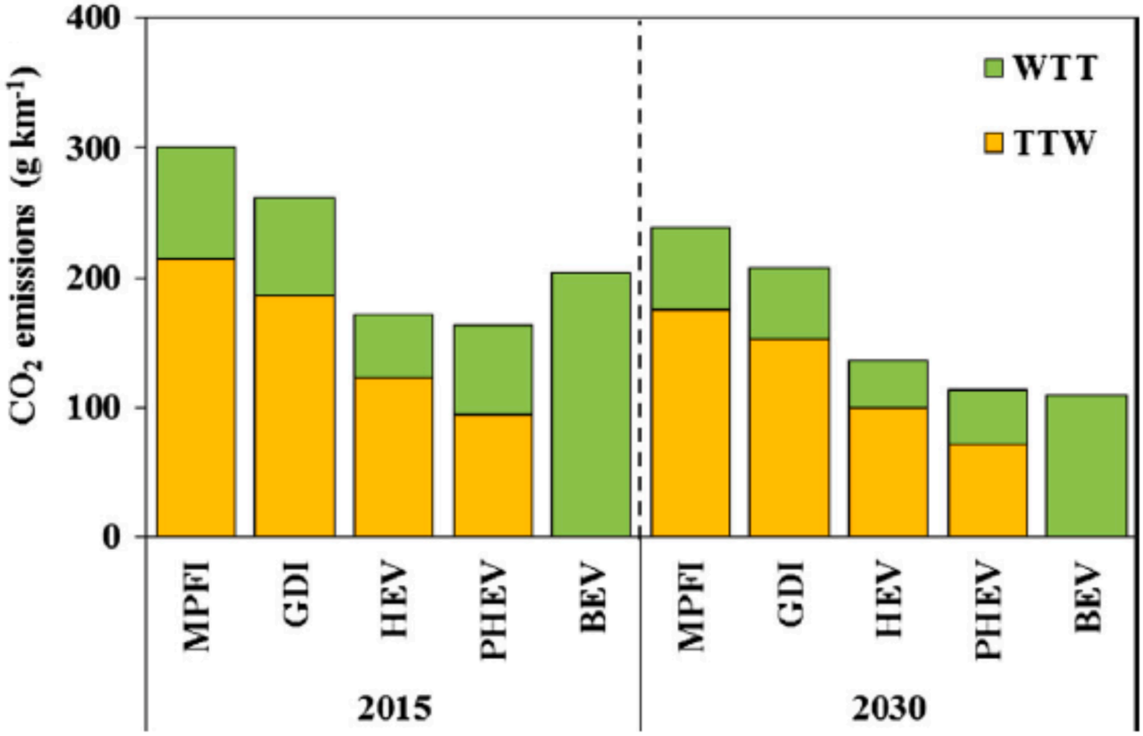


Fig. 17. Well to wheels CO_2 emissions of different vehicle technologies. MPFI: multi-port fuel injection, GDI: gasoline direct injection, HEV: hybrid electric vehicles, PHEV: plug-in hybrid electric vehicles, BEV: battery electric vehicles [117] (with permission No. 5,321,911,434,909).

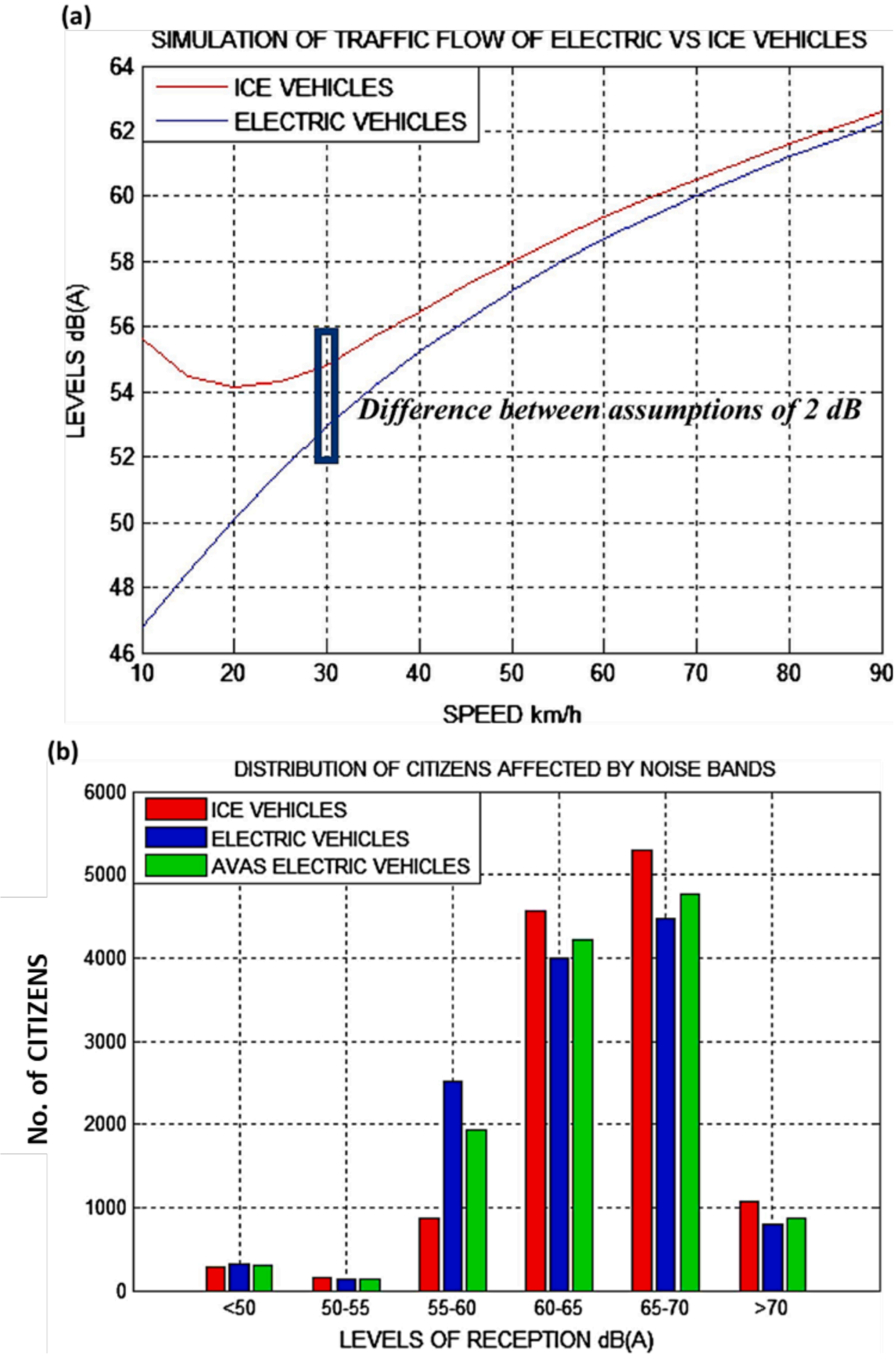


Fig. 18. (a) Simulation of traffic flow of electric vs ICE vehicles, (b) distribution of citizens affected by noise bands for 3 types of vehicles [119] (with permission No. 5,321,921,021,684). .

power [126]. EV chargers can be classified into three levels, levels 1, 2, and 3. Level 1 charger are slow chargers that use a single phase 120 V AC outlet, level 2 charging is faster and uses a 240 V AC single-phase or a 400 V AC three-phase outlet with current capacities reaching 80A. Level 3 chargers are the DC fast chargers; they use a three-phase supply that can reach 800 V AC in its latest generation and can supply 350 kW of power. Porsche is one of the first companies to make use of these charging stations in its first electric model, the Porsche Taycan [127, 128].

DC fast chargers help reduce the charging time; however, as the number of EVs increases, the high-power demand gives rise to other problems on the grid side. The increase in instantaneous power demand can cause voltage stability problems and transformer losses and induce harmonics that degrade the power quality. Harmonics occur during the power conversion by high-frequency switching gear, and they can cause electrical and thermal problems for the distribution transformers and can reduce their lifetime[127,128]. The rise in power demand from the addition of electric vehicles coupled with the evening peak load can cause grid stability problems as well as overload the transformers and cause them to deform [127]. Most EV owners start charging their cars after returning home from work, adding to the evening peak load. This is coupled with knowing that most EVs stay connected to the charging station longer than the time they need to recharge, providing an opportunity to develop smart charging strategies that optimize EV charging during the time they are connected to the grid [129,130].

As demand on the grid from EV charging increases, distribution systems are the most likely part of the utility grid to need urgent upgrades. Power generation and transmission will probably be upgraded close to their normal life cycle, given that EV shares grow gradually. Distribution Systems composed of distribution lines and transformers will need to be upgraded to accommodate the growing number of fast chargers installed [131]. Sacramento's electrical energy distribution firm conducted research and found that 17% of the transformers need to be renewed due to the extra load added by electric vehicles [132]. Distribution Network Operators (DNOs) in the UK forecast that the average maximum demand of households with slow EV charging will grow to 2 kW. They will need to plan for 2 kW per house, which is double the traditional demand [129]. Some studies have presented the negative impacts of EVs' integration into electric energy distribution systems. These are problems in the operation of the network, such as the increase in load peaks, operation outside acceptable technical limits, and increase in energy losses, in addition to the risks of worsening the quality of service and suffering penalties imposed by regulatory entities. In some countries, such as Norway, where there is a high penetration of EVs, problems have been faced in the operation of the network due to the high demand.

Distribution networks suffer technical impacts that vary according to physical infrastructure and loading. If a network experiences a load greater than that for which it is designed, it may suffer from voltages of magnitudes lower than the appropriate values and with a high loss rate. If a greater load on one or two phases and/or the conductors are arranged asymmetrically, voltage imbalance will be created in certain buses. Voltage magnitude and voltage imbalance at inappropriate levels result in damage to system loads. Additionally, the equipment used in the network has operating limits, such as the thermal limits of transformers and conductors. If these limits are not respected, the useful life of this equipment will be reduced, resulting in high costs to the concessionaire [133].

The main technical factor responsible for limiting the number of PEVs connected to the distribution network is the drop in the voltage magnitude of the system's load buses. The increase in the electrical current flowing through the equivalent impedance of the system increases the voltage drop in the distribution network.

In extended networks, the equivalent impedance tends to be higher, causing a greater voltage drop in relation to short networks. The connection of single-phase and two-phase loads in low voltage networks results in voltage imbalance. Residential charging stations are typically single-phase or two-phase, causing the voltage imbalance to vary when the EVs are connected to the grid. In some cases, when the electrical stations are connected to less charged phases of the system, the voltage imbalance of the network may decrease, but the fact is that the connection of the electrical stations is arbitrary and the tendency is that the recharging of the PEVs causes an increase in the voltage imbalance.

Distribution lines/cables and transformers are equipment designed to meet a certain demand over a planning horizon. Connecting additional loads increases the current flowing through this equipment, resulting in possible overloads and shortened life. As for electrical losses, the increase in current flowing through the conductors of the distribution networks increases this impact [134]. It was reported that charging EVs without coordination can increase the load at peak times, cause local problems in the distribution networks, and increase energy losses and voltage deviations, compromising the quality of the electricity supply. In addition, they can lead to overloads in distribution conductors and transformers, reducing the reliability of the electrical network. The work also evaluates the role played by recharge coordination in improving distribution transformer performance in feeders with low, medium and high EV penetrations [135].

LIBs are temperature sensitive as the optimum operating temperature range is between 15° and 35° C. While they can tolerate higher temperatures for a short period, prolonged exposure to temperatures above 60° C might cause the batteries to experience thermal runaway which might cause them to explode or catch on fire [70,136]. Temperature variations on cell level should be kept around 5° – 10° C, and variations on pack level should be kept around 3° – 5° C [70]. High temperatures accelerate the thermal ageing of batteries and reduce their expected lifetime [136]. Low temperatures reduce the ionic conductivity of Li-ion batteries and increase the charge transfer resistance, thus degrading the battery's performance. It might also cause lithium plating, which decreases the battery's capacity. Moreover, cold weather reduces electric vehicles' range by using some capacity to heat the cabin for comfort and heating the batteries to the optimum temperature range to maximize performance, Fig. 19 [136,137].

The relatively high initial purchase cost of electric vehicles is still a hurdle in the way of EV adoption. Electric vehicle prices have been continuously dropping in the past years, the retail price of a Ford Focus electric dropped by $10,000 between 2010 and 2015, and it dropped by $5000 for the Nissan Leaf, and by $7000 for the Chevrolet Volt . Although prices continue to drop, some studies suggest that the cost parity is still a few years ahead, between 2024 and 2025 for short-range EVs and between 2026 and 2028 for long-range EVs, as battery pack costs drop $104/kWh in 2025 and $72/kWh in 2030 [46]. The quiet operation of electric vehicles can be considered an advantage, as discussed in the previous section and can help reduce noise levels in urban areas [119]. However, at lower speeds, this might cause some risks for pedestrians, especially those who are visually impaired, because they are not able to identify incoming traffic based on sound. As a result, the United Nations Economic Commission For Europe (UNECE) has founded a regulatory group to work on regulating the noise emitted from Quiet Road Transport Vehicles (QRTV) using the Acoustic Vehicle Alerting System (AVAS) which is a synthetic sound generation system developed to be capable of real-time sound calculation and vehicle communication [138]. Another weakness for EVs compared to internal combustion engines is the lack of variety in models and manufacturers, which restricts the consumer. However, this is starting to become less important as more electric vehicle companies are emerging such as Tesla, Rivian, and Lucid, and more and more of the legacy automakers are introducing electric vehicles, such as the Mercedes EQS and the Audi E-Tron.

5.3. Opportunities for electric vehicles

The growth of electric vehicles will eventually lead to large quantities of lithium-ion batteries (LIB) that are not suitable for use in EVs anymore because their performance is no longer sufficient, and they need to be retired. An article by McKinsey & Co. expects the global second-life EV battery supply to rise from 1 GWh in 2020 to 15 GWh in 2025 and reach 112–227 GWh by 2030 [139]. This raises the need for proper End-of-life solutions for EV battery packs which present an economic opportunity if appropriately seized [139,140]. Lithium-ion battery packs pose an environmental and safety risk if they are not treated properly at the end of their life in electric vehicles [141].

There are various End-of-life options for electric vehicles; see Fig. 20. Reduction is not a retirement option; it is the process of reducing the hazardous waste in batteries. Disposal of batteries is the least energy-efficient option. Still, in certain conditions, it might be necessary due to the hazardous nature of the batteries and the risks it might expose the workers too. Incineration is not a preferred option either due to releasing

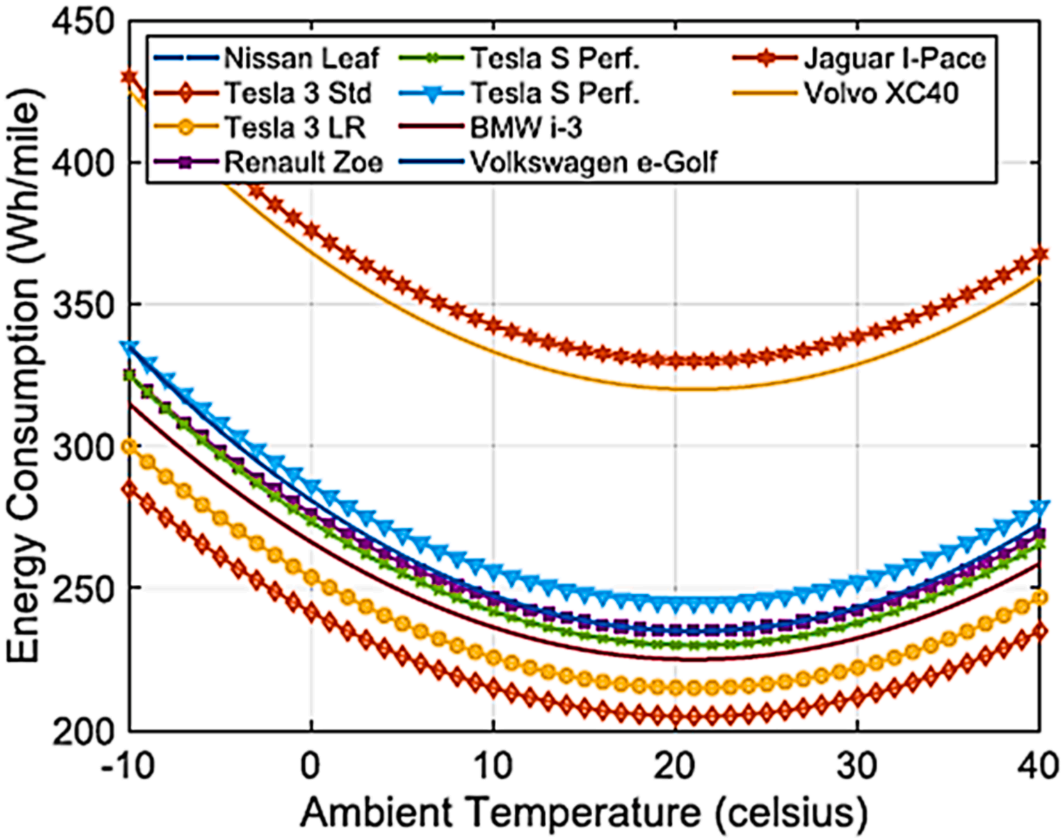


Fig. 19. The ambient temperature effect on top-selling electric vehicles' energy consumption [137] (open access).

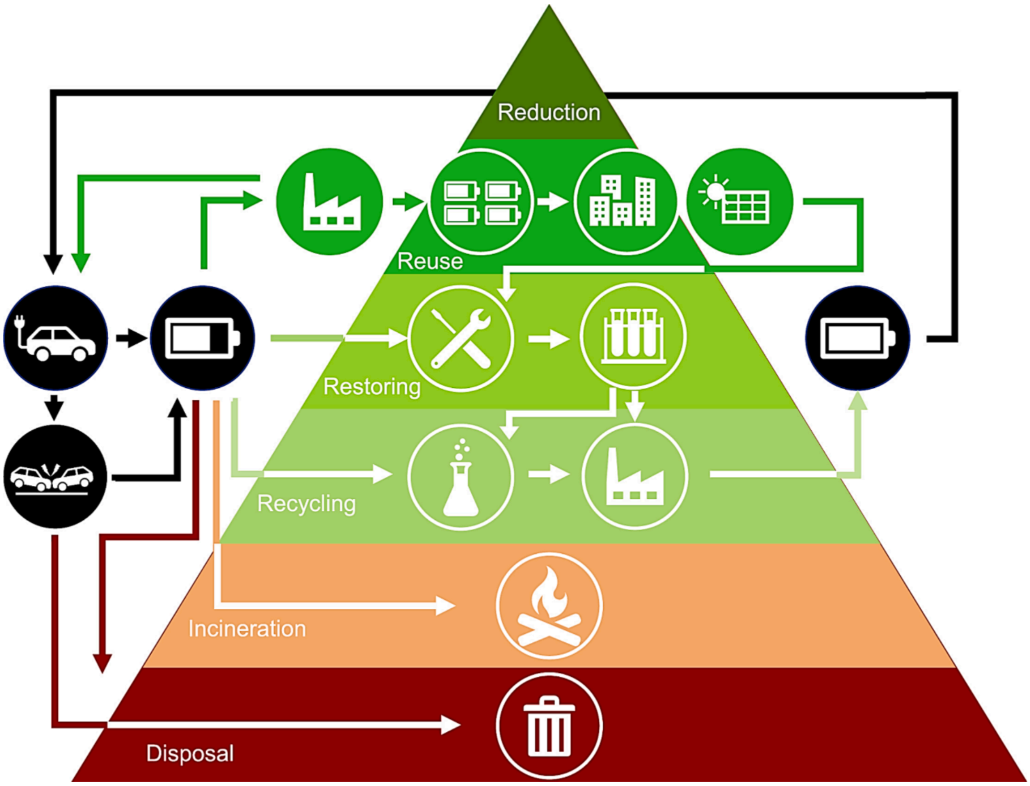


Fig. 20. Various end-of-life (EOL) options for spent EV batteries (Reduction is not a EOL option) [140] (open access).

toxic gasses into the air. Restoring batteries is another option, and it involves extracting the cathode materials from spent batteries for direct use in battery manufacturing. Reusing lithium-ion battery packs is another notable option. Reusing EV battery packs means giving them a second lease of life, whether it is in another EV or for a completely different application (cascade reuse), such as reusing them in energy storage applications [138,140,141].

Recycling LIBs is one of the most researched and important EOL options for several reasons. It is necessary to buffer the fluctuations in material costs. Balance material production because main materials production is currently dominated by a few countries; for example, cobalt production is dominated by the Congo and lithium production is dominated by Australia and China, and recycling could be a valuable source of materials [141,142]. In addition, LIBs are hazardous materials, and they require a lot of tests before transportation and shipping; a local recycling infrastructure will solve this problem [142].

Treatment of the batteries before the recycling process is a very important step that significantly improves the efficiency of the recycling process. Mechanical pretreatment starts with sorting the batteries and might include crushing or sieving the batteries. Additionally, it involves separating the unnecessary metal shroudings and plastic labels [143]. There are several recycling methods: pyrometallurgical, hydrometallurgical, and direct recycling, each with its advantages and disadvantages. Pyrometallurgical Recycling is the process of smelting spent LIBs to extract valuable metals in the form of alloys such as cobalt, copper, and Nickel. Although this is a commercially developed technique, it has certain disadvantages, such as producing toxic gases, the limited quantity of materials that can be extracted, and the high capital cost. Hydrometallurgical Recycling is the process of extracting metals from the cathode material using aqueous solutions; this process is more flexible and reliable and consumes less energy [144]. Hydrometallurgical recycling can use organic and inorganic acids; organic acids are preferred because they reduce GHG emissions produced during the recycling process by 1/8 compared to inorganic acids [144]. However, some disadvantages need to be considered, such as the risk of cross-contamination of materials; in addition, the use of inorganic acids requires large amounts of solvent and water, which can cause the equipment to corrode in the long term [141]. Also, the disposal of wastewater from inorganic hydrometallurgical recycling, which contains acids and acidic leachates, is one of the biggest problems in this type of recycling [144]. Even though hydrometallurgical recycling using organic acids is more expensive than inorganic acids, it is preferred because of its environmental benefits. Citric acids, oxalic acids, and tartaric acids are examples of organic acids used in recycling [144]. The business models of pyrometallurgical and hydrometallurgical depend on the cobalt concentration in lithium-ion batteries; as the cobalt concentration decreases the effectiveness of these recycling methods will decrease [142].

Direct recycling is directly extracting the cathode or anode materials from the electrodes of spent LIBs for restoration and direct reuse in remanufactured batteries; Direct recycling can be particularly advantageous for low-value cathodes because it avoids expensive purification steps [141]. Direct recycling has certain disadvantages, such as the fact that its effectiveness depends on the state of health of the recycled battery and the recycling steps will differ based on the type of the cathode in the battery [141]. As we head towards the electrification of the transportation sector, the development of End-of-life and second-life solutions for spent LIBs, such as recycling, that are efficient and economically viable will become increasingly important.

Wireless charging for electric vehicles is a technology that might change the way we interact with EVs. Although most EVs currently charge using cables, multiple car manufacturers such as BMW and Nissan are developing wireless charging technologies. Dynamic wireless charging technology which involves charging your car wirelessly while driving can remove EV driving range limitations if achieved and eliminate range anxiety [145]. There are three categories of wireless charging. Stationary charging systems are similar to regular charging stations but provide the advantage of not needing to plug in your car, you simply align the car with a charging pad while parking and the car automatically starts charging. Quasi-dynamic charging stations are charging stations that provide quick charging sessions in dynamic environments such as taxi stops and traffic lights. Finally, dynamic charging stations or Dynamic Wireless Power Transfer (DWPT) can charge electric vehicles while they are driving and increase their driving range [145].

Wireless power transfer systems (WPT) consist of two coils that transfer power using magnetic fields. The primary coil, which is the coil that is connected to the electricity grid generates a magnetic field using the electric current flowing through it; the secondary coil which is the coil implemented in the vehicle intercepts this magnetic field inducing a voltage which in turn generates a current flow in the secondary coil [145]. It's critical to have exact alignment between the primary and secondary coils since misalignment can reduce the power transfer efficiency [146].

Although wireless EV charging eliminates the need for wires and exposed contacts which can be considered a safety advantage, WPT systems have some safety concerns that need to be considered and addressed. One of the major safety concerns is exposure to Electromagnetic fields (EMFs). There are mainly three areas for radiation exposure; the first area is under the car, directly between the two coils, which is the most hazardous zone. The second area is around the two coils under the car. Finally, the third area is around the car [147]. Another safety concern is the exposure of medical devices worn or implanted in an individual to EMFs [147]. The distance between the coils is an important factor in controlling the efficiency of the WPT system. As the distance between the two coils increases, power transfer efficiency decreases [148]. A study showed that installing repeater coils between the primary and secondary coils can significantly improve the wireless power transfer efficiency, therefore, allowing the increase in the distance without any appreciable loss in efficiency [148]. Despite the challenges that face their implementation, wireless charging systems, especially dynamic systems, are very promising, and they can change our interaction with EVs and the transportation sector in general.

Solid-State batteries (SSBs) could possibly be the next generation of batteries. Solid-state batteries use a solid inorganic electrolyte as opposed to the liquid electrolyte in most of the current lithium-ion batteries [149]. Using a solid electrolyte significantly increases the safety of the batteries by eliminating the risks associated with using a flammable liquid electrolyte [149,150]. Another advantage of using solid-state batteries is their operating temperature range; SSBs can tolerate temperatures ranging from −30° to 100° C, which is much wider than regular LIBs with liquid electrolytes that experience a decay in the ionic conductivity of the liquid electrolyte at temperatures below 0° C and accelerated deterioration at temperatures higher than 60° C [150].

Despite the advantages of using solid-state batteries, the SSB technology is still in the research stage, and several obstacles need to be resolved before large-scale implementation. SSBs currently suffer from low coulombic efficiency and unstable cyclic performance [150]. In addition, despite the fact that, in theory, solid electrolytes are supposed to inhibit the growth of dendrites of lithium metal anodes, this is for a theoretically perfect electrolyte without any impurities, in reality, studies showed that SSBs experience dendrite growth due to the surface impurities [150,151], Lithium metal anodes haven't been widely used in batteries with liquid electrolytes because they are susceptible to side reactions and dendrite formation [138]. Dendrites form inside the solid electrolyte or at the solid-solid interface between the anode and the electrolyte and they can lead to serious safety problems by inducing short circuits [151]. The combination of solid-state electrolytes with lithium metal anode is promising to be one of the greatest advancements in the battery industry because of the previously mentioned SSB benefits and the high energy density of Li-metal anodes (theoretical energy density of 3860 mAh/g) [150,151].

In addition to the possible negative effects in terms of peak loads, the effect on the distribution system and the energy storage capacity of EVs also offers opportunities to increase grid flexibility and efficiency in the context of increasing energy generation through unpredictable renewable sources (solar and wind). To manage the difficulties of high peak loads and, at the same time, take advantage of potential synergies, it will be crucial to create a 'smart grid' that integrates smart charging and 'vehicle to grid' technology.

Smart charging technology allows you to control the timing and magnitude of power from the power supply to the EV. This technology can be used for congestion management, frequency control (including peak clipping) and charging from renewable sources. It can also be useful to use smart charging technology when electricity demand is too high, i.e. power levels can be lowered or deferred at peak periods, to reduce the load on the grid, an obvious solution for nighttime demand at high loads. V2G (vehicle to grid) technology goes a step further. This technology allows energy from EV batteries to be injected back into the grid. In addition to being able to change the moment and magnitude of the load, it is also possible to change the direction. The same technology can be used to charge car owners' homes (V2H), buildings (V2B) and more.

5.4. *Threats of electric vehicles*

The surge in battery development and production in recent years to meet the demand for electric vehicles has drawn a lot of attention to the increasing extraction of materials and the pressure it creates on material resources.

The available raw materials for battery production, especially the main constituents of lithium-ion battery electrodes, particularly lithium, manganese, nickel, and natural graphite, are enough to meet the rise in demand over the next decade. Still, they are unlikely to meet the demand for 100% electrification of the transportation sector, which further denotes the importance of recycling for material extraction [152, 153]. Lithium is one the most important materials in battery manufacturing, and fortunately, it is one of the most abundant elements on earth, it is extracted either from hard rocks or from brines. 2/3 of the world's lithium production comes from brines because compared to extraction from hard rocks, it is relatively inexpensive. Still, despite that, extraction from hard rocks continues to be a viable solution because of the slow and inefficient methodology of extraction from brines [154]. Brine extraction evaporates half a million liters of brine per tone of lithium carbonate extracted, this process is very slow and depends on weather conditions, it also depends heavily on the chemical composition of the brines which means that a long period of testing is needed before full-scale processing and production start at a plant which affects the ability of brine extraction to cope with surges in demand, this further emphasizes the need for new methods for lithium extraction from brines to help support the lithium production industry as the demand increases [154]. Another important issue is the geographical concentration of these materials. Fig. 21 shows the production concentration for the top three countries for different materials, 2015. From the figure, we can see that China dominates natural graphite production, and cobalt production is largely dominated by the democratic republic of Congo. This material mining and production concentration pose a serious supply concern as supply disruptions from one country can significantly impact the entire supply chain and might cause severe price swings [152,153, 155].

While there are varying concerns about the sustainability of supplies for battery materials, recycling could be a promising solution for material extraction, as discussed in the previous section. A study evaluating the future lithium demand through a life cycle assessment up to the year 2100 showed that by the year 2060, retired batteries could represent 320000t of lithium carbonate equivalent (LCE). If the recycling infrastructure remains underdeveloped which is unlikely, retired batteries could represent 25% of the global reserves by the year 2100 [156]. This shows that recycling could quite possibly serve as an integral part of the future material supply chain as recycling infrastructure develops and might help alleviate some of the stress from the mining infrastructure.

The surge in electric vehicle development over the past few years has been largely motivated by the environmental need to reduce greenhouse gas emissions and reduce our reliance on fossil fuels but that doesn't

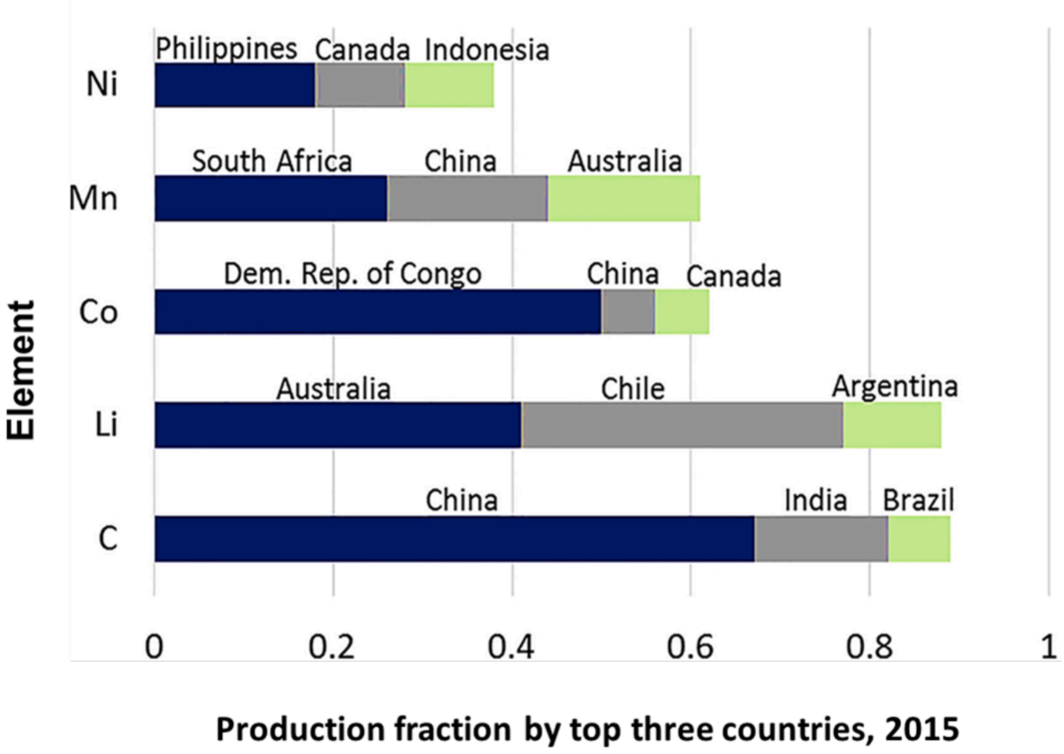


Fig. 21. Top three countries production fraction for different materials [153] (open access).

mean that the entire process of producing electric cars, especially the production of lithium-ion batteries is environmentally friendly and emission-free. Several life cycle analyses have discussed the environmental impact of battery production. Mineral extraction and metal refining are the most environmentally impactful parts of battery production [152]. Toxic leaks from nickel and cobalt mine tailings, and sulfur oxide emissions from their smelting process are examples of these environmentally impactful processes [152,157]. Hydrogen fluoride (HF) formation is one of the risks associated with lithium-ion batteries, HF forms if the electrolyte of LIBs is accidentally released in an enclosed space such as recycling facilities or tunnel car accidents [152].

The energy intensity of battery production is a big contributor to the total environmental impact in a battery's life cycle. One of the most energy-intensive parts is cathode production[157]. Fig. 22 shows the

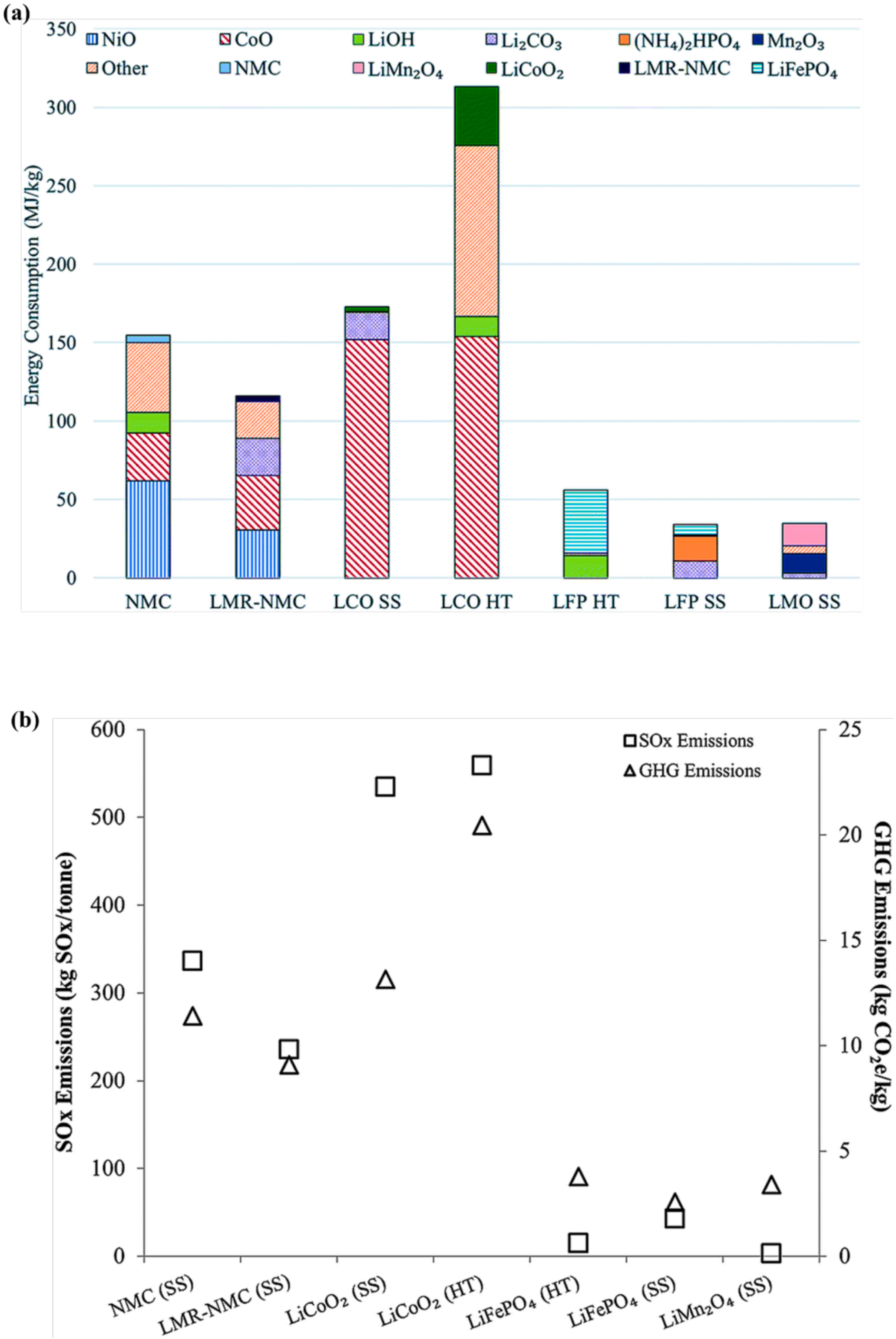


Fig. 22. (a) Cradle to gate energy consumption of different cathode materials based on different preparation processes (hydrothermal (HT) and solid-state SS), (b) Cradle to gate emissions of different cathode materials [157] (RSC, Open access).

cradle-to-gate energy consumption of different cathode materials; we can see that cathodes containing nickel and cobalt have the highest energy consumption due to their intense extraction processes. Also, from Fig. 22b, we can see that they have the highest emissions rate, whether GHG or SOx emissions, due to their previously mentioned smelting process. In addition to sulfur oxides, nickel mining has other impacts, such as heavy metal soil contamination, biodiversity loss in fish populations, and soil erosion [157]. Sulfur oxide emissions can be captured to avoid emitting it into the atmosphere. Congo is an example of a country where SO_2 emissions from cobalt and copper ore roasting are captured to produce sulfuric acid [158].

Battery production plays a big part in the environmental impact of electric vehicles and lithium-ion batteries, as mentioned earlier. According to a study, GHG emissions of the production phase of electric vehicle batteries were 50% higher than in conventional internal combustion engine vehicles in China in 2015 [159]. This high emission percentage is mainly due to fossil-fueled energy generation and the inefficiencies in manufacturing techniques, especially energy-intensive ones; improving these techniques and introducing more renewable resources to the electricity grid will help in reducing emissions significantly, the study mentioned that compared to China, the U.S. produces third of the emissions due to the improved manufacturing techniques [159]. The power mix of the electricity grid can considerably affect the GHG emissions during the electric vehicle life cycle, whether during battery production or electric vehicle operation. Several studies analysed the effect of using electricity grids with different mixes of renewable and non-renewable resources. The overarching conclusion is that grids that rely heavily on fossil-fueled power plants, mainly coal, significantly reduce the environmental benefits of the switch to electric vehicles due to the increased emission production from the power plants as a result of the increase in power demand [118,137,160–162]. Fig. 23 shows different grid configurations from different countries [160].

A comparison between the GHG production and petroleum consumption of BEVs, PHEVs, and ICVs for different power sources and electricity grids was done. It showed that unless grids are powered completely by coal BEVs, and PHEVs will offer improved emission and consumption performance compared to conventional vehicles. However, the improvements vary depending on the grid's composition and the more renewable sources in the electricity grid, the better the emission performance [157]. Upstream production of batteries, including material extraction and refining, is the driver of energy and environmental impact in the battery production process [158]. Improving these processes, whether by improving the electricity grid or by implementing more energy-efficient mining and manufacturing techniques, will help in reducing the emission and environmental impact of EVs and strengthen the position of EVs as an environmentally friendly alternative to ICVs.

In 2019 and 2020, the average price per kilowatt-hour (kWh) of electricity in the UK was around 18 pence. Data for 2021 has yet to be published, but an online quote from one of the UK's big six energy providers shows average costs of around 24p per kWh for September 2021. A car with a 50 kWh battery would cost around $12.88 (£9.50) at an average price in 2020 (considering some energy loss during charging). For 24p per kWh in September 2021, charging the same car would cost around $17 (£13), and that charge would be enough for 200 miles. Refuelling the electric vehicle will still cost half what it costs to fill up a gasoline or diesel car. However, the low price of gasoline in the United States, for example, can be a justification for the low growth in the rate of EV sales compared to European rates. One of the EV threats is the expected increase in the electricity price. With 10 million EVs worldwide, the electricity price doesn't change. But it is expected to gradually increase the electricity price with the increasing demand for EVs. This will be a threat that slows down the demand for EVs [163].

6. SWOT analysis of battery application in the automotive industry

This section will explore the SWOT analysis of battery applications, specifically in the automotive industry. SWOT is a multi-criteria decision tool used in various applications. For example, it was used for batteries and photovoltaics end-of-life treatment [164,165]. SWOT analysis is designed to identify the barriers and came up with the best recommendation for 100% of electrification of transportation sections by car. Fig. 24 captures the various SWOT analyses of battery electric vehicles, elaborated in subsequent sections.

6.1. Strength analysis

6.1.1. S1: cheaper price for distance covered

Except for the initial cost needed in purchasing the vehicle, running a vehicle over a distance using electricity has some merits. For instance, in Brazil, the unit cost for cars powered by ethanol and gasoline was expensive compared to those powered using electricity in 2019. Vehicle efficiency and fuel costs were 13.12 km/L and US$ 1.20/L for gas. These in terms of ethanol within the same period in the year stood at 9.02 km/kWh and US$0.80 L. On the other hand, Battery-powered electric vehicle, in terms of vehicle efficiency and fuel cost, was 5.5 km/kWh and US$0.14/kWh. The same phenomenon is the case in the United States, where the price of power needed to reach a specific distance with a BEV was lower than gasoline-powered vehicle [166]. Shanghai also reported a similar scenario where it was 41 percent cheaper to use battery electric vehicles than that powered by gasoline and ethanol [167].

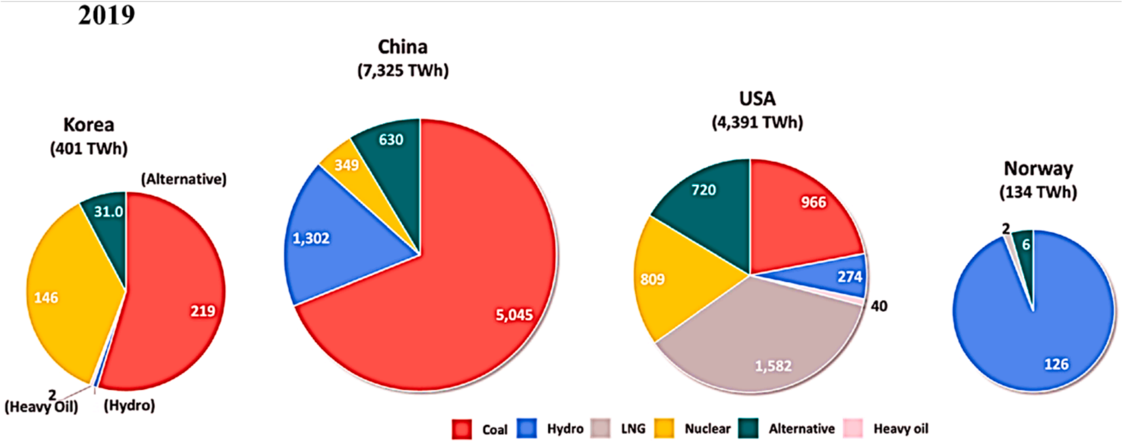
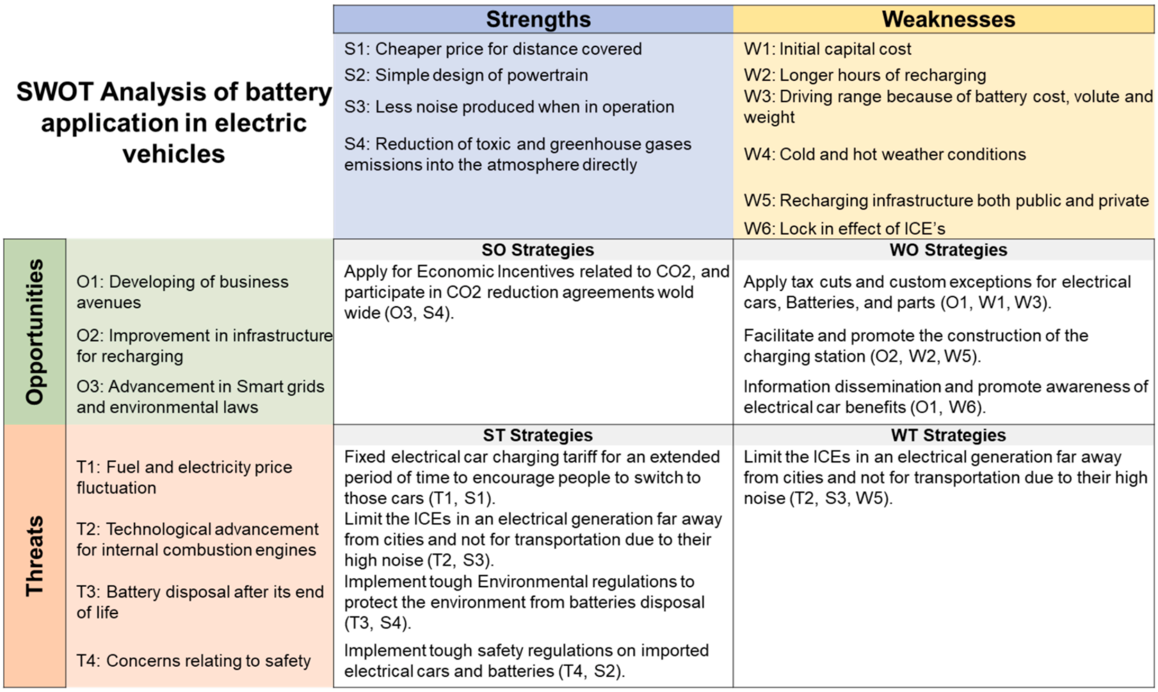


Fig. 23. Electricity generation configuration from different countries [160] (with permission 5,322,020,027,584).



SWOT Analysis of battery application in electric vehicles		Strengths	Weaknesses
		S1: Cheaper price for distance covered S2: Simple design of powertrain S3: Less noise produced when in operation S4: Reduction of toxic and greenhouse gases emissions into the atmosphere directly	W1: Initial capital cost W2: Longer hours of recharging W3: Driving range because of battery cost, volute and weight W4: Cold and hot weather conditions W5: Recharging infrastructure both public and private W6: Lock in effect of ICE's
Opportunities	O1: Developing of business avenues O2: Improvement in infrastructure for recharging O3: Advancement in Smart grids and environmental laws	**SO Strategies** Apply for Economic Incentives related to CO2, and participate in CO2 reduction agreements wold wide (O3, S4).	**WO Strategies** Apply tax cuts and custom exceptions for electrical cars, Batteries, and parts (O1, W1, W3). Facilitate and promote the construction of the charging station (O2, W2, W5). Information dissemination and promote awareness of electrical car benefits (O1, W6).
Threats	T1: Fuel and electricity price fluctuation T2: Technological advancement for internal combustion engines T3: Battery disposal after its end of life T4: Concerns relating to safety	**ST Strategies** Fixed electrical car charging tariff for an extended period of time to encourage people to switch to those cars (T1, S1). Limit the ICEs in an electrical generation far away from cities and not for transportation due to their high noise (T2, S3). Implement tough Environmental regulations to protect the environment from batteries disposal (T3, S4). Implement tough safety regulations on imported electrical cars and batteries (T4, S2).	**WT Strategies** Limit the ICEs in an electrical generation far away from cities and not for transportation due to their high noise (T2, S3, W5).

Fig. 24. SWOT analysis of battery electric vehicles.

6.1.2. S2: simple design of powertrain

The powertrain for battery electric vehicles is not cumbersome compared to other powertrains. For instance, there is the absence of a unit of equipment coupled in series, unlike gasoline powertrains. The omission of internal combustion engines, starter, gearbox, etc., simplifies their operation [168]. Similarly, the absence of moving parts in battery-powered electric vehicles coupled with fewer components integrated on this powertrain implies lower fluid is needed for the entire system since engine oil, fluid for transmission, and a cooling medium are not required. These factors ensure that the whole powertrain is lower in battery electric vehicles than the others like the diesel or gasoline powertrains [169].

6.1.3. S3: less noise produced when in operation

Due to the absence of more moving parts in battery-powered vehicles, they operate without noise, making them suitable for urban applications. In a way, This is likely to improve the quality of life in urban areas and reduce health issues associated with noise pollution like cardiovascular disease, sleeping disorders, etc.

6.1.4. S4: reduction of toxic and greenhouse gases emissions into the atmosphere directly

Omitting pollutants released into the atmosphere when producing various components and the vehicles themselves for battery electric vehicles and the sources of electricity, battery electric vehicles do not emit toxic materials directly into the atmosphere, be it the location of driving the car. This is not the case for internally powered vehicles, where particulate matter is released and soot when in operation, improving the general populace's health and overall lifestyle [170].

The power required to power the batteries for BEVs is often argued as the primary source of toxic emissions into the atmosphere, but the narrative becomes different if the power source is obtained from renewable sources [168]. So for a country like Brazil, which reported significant progress in 2018 in ensuring 83 percent of the power consumed was from renewable sources, the utilization of battery-powered electric vehicles will significantly ensure a complete reduction in emissions from the transport or automotive sector in the country [171].

6.2. Weakness

6.2.1. W1: initial capital cost

The main challenge impeding the commercialization of EVs is the initial cost of acquiring the product compared to vehicles with internal combustion engines. The utilization of materials that are light in weight coupled with battery cost is a critical element that adds to the overall cost of the technology. These components, i.e., the batteries and lightweight materials based on the data gathered, are responsible for nearly 30% of the total cost of the vehicles [125]. Studies have shown that the initial cost of battery electric vehicles has created lots of dissatisfaction in the sight of several potential buyers globally [125].

6.2.2. W2: longer hours of recharging

One of the key issues limiting the commercialization of battery electric vehicles is the general perception of a long waiting time when recharging the batteries. This has been a long-standing issue that has negatively impacted the technology's adoption. Most users and the general populace argue that the time required to wait for the complete charge of the battery is a waste of productive hours coupled with restrictions on movement [125].

6.2.3. W3: driving range because of battery cost, volume, and weight

Considering the case of lithium-ion energy storage units, there are often considerable losses in terms of power and energy density concerning time. This has a negative effect on the driving range, efficiency, and recharge time [172]. Similarly, the cost that comes to play when users of battery electric vehicles want to replace these energy storage units, particularly outside the car's warranty, is all factors discouraging its accelerated commercialization [172].

Battery cost, which is often measured in terms of cost per kWh coupled with energy storage capacity, has compelled most manufacturers of BEVs to produce vehicles with a shorter driving range [173]. Even though the vehicle's driving range could be extended via an increase in battery numbers, this approach has a detrimental effect on the weight of the car and a decrement in the vehicle's space [174]. An increment in the battery's weight will imply modification of the vehicle's suspension coupled with the braking system. The weight will also compromise the performance and require electric motors with higher characteristics leading to an increment in cost. All these changes in terms of the weight will also imply more energy being to propel the vehicle over a shorter distance [175].

6.2.4. W4: cold and hot weather conditions

Two primary issues regarding the weather's impact on electric vehicles come into play. Under cold weather conditions, the battery's efficiency is reduced significantly, and using a heater directly affects the driving range. In the lithium-ion battery's case, a temperature decline is likely to impact the power density. This phenomenon will cause the energy that must be supplied when accelerating to be reduced and affect regenerative braking. Issues about longer recharging hours cannot be ignored. Using a heater is one factor that reduces the driving range when the weather is cold, as a considerable amount of energy is extracted to meet this demand [176]. In hotter regions, using air conditions harm the battery electric vehicles. Commonly, a compressor is linked to a motor, which enormously reduces battery energy [177].

6.2.5. W5: recharging infrastructure, both public and private

Even though recharging electric vehicles is possible at home, there is a gap in developing public recharging infrastructure for battery electric vehicles [178]. Even though one may argue that there is no need to invest in the infrastructure because the technology is not yet commercialized fully, its acceptance globally will be more accelerated if the infrastructure required is well established globally [179]. Making a private recharge point will need homes to have a parking lot owned privately with an electrical outlet. Though this is feasible, it becomes challenging if, during the development of the house, recharge points were not factored into the design of the edifice [180]. Talking of infrastructure, there is currently not enough consolidated network of services and products dedicated to developing battery electric vehicles. The investment required to make this a reality will also come with the need for specific time allocation. Sadly, most investors do not invest in a project without the assurance of recouping the investment back over a period of time while consumers who want to acquire BEVs will reconsider their decision with specialized services, leading to the creation of a lock-in effect [179]. IC engine power vehicles, on the other hand, have well-developed filling stations, dealerships, repair shops, auto parts, etc., making them more convenient to owe one than BEVs.

6.2.6. W6: lock in the effect of ICEs

When one technology solely depends on another technology, there is a significant likelihood of this lock-in effect if one technology is matured. This scenario usually causes the dominance of one technological concept over the other. It is typically expected in the automotive sector, especially ICEs and other propulsion systems. This phenomenon discourages prospective users from considering a change in the technology they use because of the time and cost committed to the existing concept. Again, some manufacturers tend to profitably from economies of scale and investments in R&Ds. This, from academic parlance, is referred to as technological lock-in. These are all key factors making the commercialization of BEVs challenging [181].

6.3. Opportunity

6.3.1. O1: developing business avenues

As defined by Schumpeter, entrepreneurship is an important element in the world that utilised added value coupled with identifying business opportunities to meet a specific demand, ensuring a higher profit is attained [182]. With the sole goal of making profits, the entrepreneur considers coming up with a product and services via novel arrangements. This brings about innovation as well as creates more business opportunities. With the battery electric vehicles earmarked as a business avenue that would yield profits, prospective investors could target this sector.

6.3.2. O2: improvement in infrastructure for recharging

With significant research activities, the cost of batteries is likely to decline with respect to time, especially in the case of lithium-ion batteries. Between 2000 and 2018, its price declined tremendously, with its cost in 2010 being higher than the cost in 2018 by one-sixth. This trajectory is anticipated to progress for a more extended period because of an enhancement in the process during its production and the evolution of novel technological concepts [183].

There is currently contrasting competition between batteries used in the automotive industry and used in other applications like laptops, phones, etc. This phenomenon, in principle, attests to the need for enhancing battery characteristics via active research. Lithium-sulfur and air batteries are areas that can be considered for future work.

To accelerate the commercialization of BEV, there should be a massive investment into recharging stations and infrastructure across urban and rural areas. Ideally, these charging stations should be centered around well-known cities and regions and should instead be across rural areas. Companies in charge of replacing discharged batteries should be institutionalized as this will reduce the driving range for the vehicle and the time needed for charging the batteries. There is still the need for several investigations to make this battery swapping concept possible. There is also the need for a wireless dynamic recharging option where the vehicle can be charged when driving. This will increase the driving range for battery electric vehicles [145].

6.3.3. O3: advancement in smart grids and environmental laws

Developing novel smart grids capable of recharging without overloading the electrical system is very important. The advancement of this concept, mainly for storing and producing electricity via an approach called vehicle to the grid, is the future for this sector. This will ensure that the owners of BEVs get some money by selling some of the stored energy in the batteries back to the grid, while excess energy from renewable technologies could be stored intermittently. With the current laws on emissions from the automotive sector becoming stringent, battery electric vehicle is undoubtedly the available option to salvage the situation as this will improve the quality of air and reduce greenhouse gases.

6.4. Threats

6.4.1. T1: fuel and electricity price fluctuation

The fuel cost for ICEs is unstable but has often been subsidized by most government bodies across the globe. The Russia and Ukraine war has even escalated issues further as most global economies are crushing down hence making fuel extremely expensive. Other factors affect the prices of fossil products like supply and demand and end economic and political factors. The current cost of fossil products restricts the attractiveness of different energy sources, making it difficult for customers to switch to other concepts technologically [178]. A possible replacement for internal combustion engines is affected by the cost of petroleum. This can significantly affect having a suitable replacement for battery electric vehicles, mainly if there are political and economic impacts associated with the directives. Most countries currently still struggle with developing infrastructure for battery electric vehicles globally. It must be noted that the development of infrastructure for the technology will come at a cost that will have a ripple effect on the cost of power. The other challenge is the need for some changes in the electric power system to augment the load. However, from the microeconomic point of view, this implies that there should be a need for supply and demand, which will increase the cost of electricity [184].

6.4.2. T2: technological advancement for internal combustion engines

The technological advancement in ensuring the improvement of internal combustion engines makes the commercialization of battery electric vehicles nearly impossible because these novel ICEVs are designed to be environmentally friendly hence the need for BEVs within the society is likely to dip with time if drastic measures and structures are not put in place.

6.4.3. T3: battery disposal after its end of life

Lithium-ion batteries are made up of heavy metals and toxic electrolytes during their end of life pose a threat when these cell components are exposed to the immediate environment. This could easily cause the water table to be polluted, especially if kept on a landfill site. Similarly, incineration is also likely to cause the emission of toxic gases into the environment [185].

6.4.4. T4: concerns relating to safety

The safety of batteries is secured provided they don't discharge higher voltages beyond their threshold, toxic gases, exposure to a higher temperature, and fire. There have been some concerns about the type of electrolyte used in manufacturing these batteries for BEVs. Some of these electrolytic mediums are flammable, and when exposed to elevated temperatures, they could spark fire [186]. This is likely to be the case when the car collides with another vehicle, as was reported in 2013, especially with Tesla cars. There are some issues about safety in the case of battery electric vehicles. There are pertinent issues raised in relation to electric shock and a risk due to the chemicals used in manufacturing the batteries when they come into contact with fire, corrosive agents, etc., capable of causing the battery to explode. During recharging, there is some risk that must also be considered as there is an intensification of a chemical reaction and a direct connection of the vehicle to the power grid. There are some issues from a mechanical point of view as the car's weight correlates to the weight of the battery; hence, during an accident, the vehicle's impact is likely to be greater if the car becomes stable under these conditions [187].

Investigation into predicting the useful life of the cell and remaining useful life via a reduction in chemical degradation should be the direction for active research activities. This coupled with the utilization of non–flammable electrolytes, would significantly change the sector. Some of these studies have also focused on solid-state batteries. These batteries have been reported as safer because they are less susceptible to catching fire and have higher energy and power density. They also exhibit higher chemical and thermal characteristics. They also have a longer life span, which is the main factor for the increased research activities in this area [188].

6.5. Comparing key factors of the SWOT matrix

6.5.1. Strength and opportunities – utilization of strength to capture opportunities

Approaches for increasing fossil product costs and tighter environmental laws can be adopted to improve the demand for electric vehicles and change the public perception. Some key elements that would come into play under such a scenario are the lower cost per unit of distance travelled, the lesser release of toxic emissions, and a decrease in greenhouse gases (S1, S4, O4). Merging a simpler powertrain coupled with the merits associated with production at a large – scale is useful in reducing the market price of the vehicles, other systemic components, and the cost of batteries, hence making battery electric vehicles cost-effective compared to different types of powertrains (S2, O1). Further study into enhancing battery performance is significant, particularly in the vehicle's driving range. This, coupled with a reduction in recharging time, will increase its commercial viability, especially with the entire operation being very silent. The evolution of wireless charging will also reduce frequenting stations, growing public acceptance over time (S3, S4, O2, O4).

6.5.2. Strengths – threat: using strengths to curb the possibility of threats

The cost of power and fossil products directly correlates to the battery-electric vehicles' lower cost per unit of distance travelled. This merit is reduced due to a decline in fossil product prices and an increment in the cost of power because of a sharp decline in the reliance on fossil products to sustain significant economies globally. Other queries elucidated have to do with the demand for electricity due to the growing demand for battery electric vehicles. These factors are the main concerns reducing the public acceptance or replacing existing fossil-based powertrains. To mitigate these challenges, there should be an increment of taxes on fossil products as well as a modification of power systems should be initiated to curb the higher demand for power beyond what is being supplied (S1, T1). The evolution of hybrid vehicles is also likely to cause significant problems because they utilize the merits of BEVs and IC vehicles in the development of the powertrain. Manufacturers of these powertrains must be clear to the customers about the cost of maintenance associated with these powertrains and the complexity of the driving systems (S2, S4, T2). The environmentally friendly nature of battery electric vehicles, i.e., non–emission of direct pollutants and a decline in greenhouse gas emissions, are some notable positives of BEV, especially if the electricity source is a renewable source (S4, T3).

6.5.3. Weakness – opportunity; enhancing weakness by taking into account opportunity

In the last few decades, as explained earlier, there has been a significant decrease in the cost required to buy battery electric vehicles and a decline in the cost of maintaining the battery. From 2010 to 2018, there has been a decrease in cost per kWh for lithium-ion energy storage units by 85 percent. This has, however, been projected as the case futuristically. However, the design of battery electric vehicles should be improved further compared to IC vehicles (W1, O2). Technological advancement in terms of electricity storage has improved significantly, particularly concerning energy and power density and safety issues. Improvement of this phenomenon is needed in overcoming 3 primary challenges of battery electric vehicles, namely drive range, a longer time for recharging, and fire hazards. The development of cars that are safe to use but deliver a higher driving range is important in enhancing the rate of availability of the vehicles and improving the time needed during recharging of the car. The demand for a more extended driving range should be tied to the need for lesser recharging facilities (W2, W3, W5, O2). A technological lock is also another issue negatively impacting the commercialization of battery electric vehicles. To change the narrative, there is currently the need for entrepreneurial activities to develop novel businesses that will yield profits and replace the dominating technology. This is likely to cause start-up businesses and corporations to spring up in the development of battery electric vehicles (W5, O1).

6.5.4. Weakness – threats: approach that is capable of reducing weakness but avoiding threats

Most consumers in the automotive industry would prefer hybrids because they tend to combine the power/merits of internal combustion engines and conventional vehicles. Significant factors like a decrement in fossil-based products, upward adjustment of electricity prices, and enhancement of ICEs are all factors that could accelerate the adoption of hybrids at the expense of battery electric vehicles by the public. Enhancement of electricity storage technologies is more likely to reduce the price per kWh but improve energy density and durability in other to change battery electric vehicles to make them more attractive than hybrid powertrains. Despite the progress made in fuel cell technologies, there is still more room for significant improvement before being competitive enough to be considered a replacement for battery electric vehicles or even the conventional type of vehicle (W2, W3, T1).

6.6. Strategies to 100% electrification of car transport

For any government planning to 100% electrification of car transport in any country authors recommend the following strategies:

1 Apply for Economic Incentives related to CO_2, and participate in CO_2 reduction agreements worldwide (O3, S4).

2 Fixed electrical car charging tariff for an extended period of time to encourage people to switch to those cars (T1, S1).
3 Limit the ICEs in an electrical generation far away from cities and not for transportation due to their high noise (T2, S3, W5).
4 Implement tough Environmental regulations to protect the environment from batteries disposal (T3, S4).
5 Implement tough safety regulations on imported electric cars and batteries (T4, S2).
6 Apply tax cuts and custom exceptions for electric cars, Batteries, and parts (O1, W1, W3).
7 Facilitate and promote the construction of the charging station (O2, W2, W5).
8 Information dissemination promotes awareness of electrical car benefits (O1, W6).

7. Recommendations and future perspectives

This paper analyses the overall status of electric vehicles regarding strengths, weaknesses, opportunities, and threats. Based on this analysis, the following recommendations are made:

- Policies and government incentives supporting the transition to alternative fuel vehicles should be tailored based on the type of technology, whether it is for battery electric vehicles, plug-in hybrid electric vehicles, or other technologies, instead of generalized policies that don't account for the differences between these technologies and their different levels of contribution to the reduction of GHG emissions and the differences in attractive factors for the consumer, as suggested in [189].
- Building the charging infrastructure and network is imperative to the development of the EV market. Centralizing the network information and keeping it up to date in terms of locations and active and inactive stations in an easily accessible manner for the end-user, and improving payment interoperability between different networks are key factors in encouraging the adoption of EVs and should be given extra care and attention by governments as suggested in [120,126].
- The increased electricity demand in the coming years caused by the increased share of electric vehicles should be accompanied by an increase in the share of renewable energy resources in the electricity grid and reducing the dependency on oil and fossil fuels to avoid increasing the emissions generated during their charging and offsetting the environmental benefits of EVs by increasing their well to wheels emissions.
- Distribution systems in local electricity grids should be constantly monitored and upgraded when needed to ensure the flexibility of the grid and its ability to withstand surges in demand caused by EVs. As mentioned in [131] transmission lines and transformers are the most likely part to need constant upgrades to accommodate the growing number of EVs and charging stations. These upgrades will help improve the grid's ability to withstand surges in demand and endure extreme weather conditions to avoid unwanted interruptions or blackouts.
- Recycling is going to play a major role in the future of the battery industry and is needed to ensure the sustainability of the materials supply chain. Materials needed for battery manufacturing are not enough for 100% electrification of the transportation sector coupled with geographical concentrations in material extraction and refinement [153,155,190] means that extraction of materials from recycled end-of-life batteries is needed, and extra effort should be allocated to improve existing methods and develop new commercially feasible recycling methods. Countries should aim at increasing their efforts in recycling and developing of recycling facilities because as the share of EVs in the transportation sector increases so as the future retired batteries, as mentioned in [156] and if each country increases its share of extraction from recycled materials this will eventually help alleviate some of the pressures from the geographical concentrations of mining and refining.

8. Conclusion

The present study delved into the current state of batteries in electric vehicles and the prospects of power electronic converters in the automotive industry. It has been deduced that the future of the EV industry will mainly depend on its cost, efficiency, and performance. The study further explained how with the demand for comfortability in these vehicles, the load required tends to go up incrementally. Only a battery unit cannot deliver this high demand as a normally varying rating of power is required. The bidirectional DC-DC converter was discussed as a suitable option to meet this demand. The investigation further evaluated the strength and weaknesses of an electric vehicle holistically based on the system components. SWOT analyses have been carried out on the battery in EVs. Based on this analysis, the recommendation for reducing weakness while avoiding threats were given. Moreover, strategies to 100% electrification of car transport were introduced. Despite the success chalked in recent times, there is still more room for improvement, hence the need for further studies into battery technology and power electronic converter technologies to reduce the overall cost of the system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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